DEVELOPMENT OF GUIDELINES FOR SYSTEMATIC PLANNING, DESIGN, OPERATION AND MAINTENANCE OF NIGHTTIME LINEAR CONSTRUCTION ILLUMINATION SYSTEMS

By

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DEVELOPMENT OF GUIDELINES FOR SYSTEMATIC PLANNING, DESIGN, OPERATION AND MAINTENANCE OF NIGHTTIME LINEAR CONSTRUCTION ILLUMINATION SYSTEMS

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Chairperson: Ralph D. Ellis, Jr.
Major Department: Civil Engineering

It is estimated that over 20% of the work on our nation's highways is being done during nighttime hours to alleviate traffic congestion. Proper design and employment of work zone illumination systems contributes to safety, quality, productivity, and, ultimately, cost effectiveness.

This dissertation presents the development of guidelines for illumination of nighttime linear construction such as highways. It provides a tool that can be used by the contractor and inspecting agency to design and configure or validate proposed illumination systems while satisfying existing or any foreseeable design criteria. It also addresses the comfort and safety of the passing motorist through a systematic procedure for the reduction of glare.

Proper operation and maintenance of the illumination system are essential for continued effective service. These factors are discussed as well as cost elements that will influence any economic considerations.

Use of the design procedure and glare criteria is demonstrated through a case study of a typical highway repair project in which three different approaches are taken to the illumination problem. Temporary, portable, and equipment-mounted lighting systems are discussed as the solutions to the design problem.

CHAPTER 1
INTRODUCTION

Problem Statement

A major problem facing both contractors and government agencies involved in nighttime highway construction activities is the selection and configuration of light sources such that required levels of safety, productivity, and quality are achieved in accordance with the terms of the contract specifications.

There are presently two approaches to this problem. Sophisticated lighting design software can be used to model the construction work zone. Although most of the currently available computer lighting design software packages have more of an architectural orientation, if certain required features related to outdoor lighting are available, they can be readily adapted to the dynamic characteristics of a construction work zone. Another option would be to utilize simplified design procedures available from most lighting manufacturers. Difficulties with this method are that many existing procedures lack any degree of precision, are often product-oriented for the specific manufacturer, and are usually based on rather limited and fixed parameters such as mounting heights, locations, and tilt that do not necessarily correspond to conditions typically encountered on a highway construction site.

Neither one of these options is, therefore, particularly appealing to the contractor. The former requires purchase of specialized software with rather limited utility or the engagement of a lighting engineer. The latter does not necessarily ensure an adequate design that will satisfy all illumination criteria. From the perspective of life-cycle planning, the problem is further exacerbated by a lack of information regarding the proper use and operation of the system. If the intended users have no appreciation for the significance or reasons for specified parameters, there is a tendency for a careless implementation.

What is needed, then, is a guideline that will lead the contractor or owner through all phases of the illumination problem to include planning, design, operation, and maintenance of the necessary lighting system. With a basic understanding of visibility requirements and equipment performance characteristics, the contractor can configure the lighting through the application of simplified computational procedures while maintaining an acceptable level of confidence that specified illumination standards are being satisfied.

Several factors influencing the basic illumination problem can be identified by using a commercially available lighting design software to simulate construction site conditions and parameters such as mounting height and tilt. If the relationships between these parameters can be quantified, the development of simplified procedures based on construction work zone parameters is feasible.

At a minimum, the design methodology will require the following information:

1. Specified illumination levels
2. Area to be illuminated
3. Light source performance characteristics

The methodology will also be used to evaluate potential glare and develop recommended configurations.

It is anticipated that the guidelines will be used by construction field personnel with very limited or no illumination background. Therefore, important criteria in the development are completeness, versatility, simplicity, and robustness. It should be easy to understand and use. Any light source that might appear on a job site should be accommodated by the procedure.

Background

The nation's infrastructure is faced with a crisis on two fronts. A system deteriorating with age has also failed to keep pace with the demands of an ever-growing population. Looking at the highway system best illustrates this fact. As reported by the Federal Highway Administration (1991), approximately 9% of the nation's interstate highway system is in "poor" condition. In Florida, nearly 18% or 6,000 lane miles of the state's highways are reported to be in need of resurfacing or repair. More than 1,300 bridges, 24% of the total, are also considered deficient. An unprecedented demand due to population growth results in 27% of the state's highways being considered congested while 44% regularly have major congestion problems (Partners in Productivity Task Force, 1988).

Emphasis in the highway industry has shifted over the last few years from building new facilities to maintaining and improving those in service. These activities have created heavy congestion on roads already loaded to capacity. To minimize the adverse effects on the public, such as exposure to delays or inconvenience and safety hazards, nighttime operations have been successfully employed on numerous occasions around the country. Analysis of the volume distribution on a typical three-lane freeway and the estimated work area capacities at different times of the day, as shown in Figure 1.1, indicates that approximately 6 nighttime hours are available where congestion is minimum and two lanes could be closed. Approximately 20% of the work being performed on the nations highways and bridges is now being done at night (Federal Highway Administration, 1985).

As a result of this increased interest in nighttime activities, renewed emphasis has been placed on research into

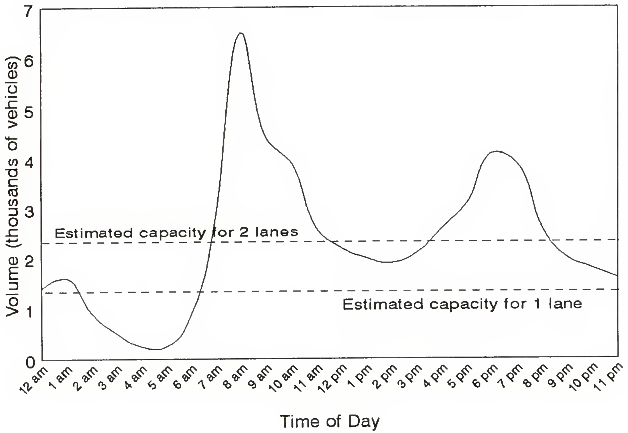


Figure 1.1 Volume distribution for 3-lane freeway (Federal Highway, 1985).

the issues relating to safety, quality, and productivity associated with nighttime work. Results have been inconclusive. Some projects have reported an increase in accidents, either construction or traffic related, while others have reported decreases or no significant changes. Similar finding have been reported for quality and productivity. In a 1991 study it was determined that no statistically significant conclusions could be drawn regarding the difference in the production rates for the milling of existing pavement (Ellis & Herbsman, 1991). This is not surprising and serves to confirm the complexity of the nighttime construction environment.

Illumination standards for the construction industry are not well defined. Discussions with the Industrial Lighting Committee of the Illuminating Engineering Society of North America (IES) indicate no record of research in this area. Research that comes close to filling the needs of the construction industry was performed in the early 1970s as mandated by the Coal Mine Safety and Health Act of 1969. It took 7 years of investigation, research, testing, and evaluation to develop illumination standards for mines.

Lighting is the least studied and most critical aspect of nighttime construction. Weston first reported the important relationship between illumination and industrial efficiency in 1935 (Weston, 1935). It has proven difficult to study because of the subjectivity and psycho-physiological nature of the measurements involved. Until such time that good lighting practices are implemented at construction sites, there is limited value in attempting to measure productivity, quality, and safety with respect to daylight performance standards.

Computer-aided design of lighting configurations is the currently accepted practice. Most of the recent analyses have been limited to evaluation of horizontal illumination and uniformity levels using architecturally based software. Very few of the available packages have the capability to directly evaluate glare. On highway construction projects in particular, glare is a subject that cannot be overlooked. It poses a threat to the safety of not only the workers but also passing motorists. The proposed guideline is unique in the development of construction work-zone-oriented parameters while considering and making adjustments for the negative effects of glare.

Success of the ensuing research is not predicated upon development of specific illumination standards for construction sites. Considering the experiences of the mining community, these standards might not be realized for many years. For this reason, the methodology to be developed should be very flexible and adaptable to any specified performance standard.

Objectives

Based on the ever-increasing amount of nighttime highway construction, it becomes imperative that a research effort be initiated that facilitates the implementation of quality illumination plans. Objectives of this research include development of guidelines that will enable the construction industry to provide and maintain adequate illumination systems for nighttime highway work zones, thereby improving productivity, quality, safety, and, ultimately, cost effectiveness. Specific objectives are as follows:

1. Review lighting concepts as they relate to the visual task.
2. Review current nighttime construction practice.
3. Evaluate available light sources and assess their capabilities in a construction environment.
4. Develop a robust manual design process based on work zone geometry and light source characteristics that is simple to use.
5. Provide recommendations for the proper operation and maintenance of lighting systems in a construction environment.
6. Assess the potential economic impact of illumination systems on construction costs.
7. Validate the accuracy of the process and determine what sensitivity there is to potential variation in parameters.

8. Demonstrate the practicality and utility of the guidelines.

Successful accomplishment of these objectives should result in a significant contribution to the construction industry.

Research Methodology

In order to accomplish the research objectives, the investigation is organized into the four distinct phases shown in Figure 1.2.

Phase I--Survey

Providing a clear and accurate assessment of the historical background and current state of the art will assist in determining the necessity of the proposed guidelines and ensure technical accuracy. In this phase a detailed literature survey was conducted to ensure the employment of current technology. A computerized search from the Southern Technology Application Center (STAC) resulted in more than 100 published papers and articles. Additional reference materials were obtained through the Illumination Engineering Society of North America (IESNA) and the International Commission on Illumination (CIE). Although a very limited number of articles were found specifically addressing the topic of construction work zone illumination, there were quite a few in related areas such as industrial

PHASE I SURVEY

Scope	Chapters
Historical background and current state of the art	1. Introduction 2. Visibility Requirements

PHASE II ANALYSIS & DEVELOPMENT

Scope	Chapters
Developing an understanding of the critical relationships	3. Selecting Lighting Equipment 4. Configuration of the Lighting System 5. Designing the Lighting System

PHASE III IMPLEMENTATION

Scope	Chapters
Effective use of the lighting system	6. System Operation and Maintenance

Phase IV EVALUATION

Scope	Chapters
Evaluate the guidelines in terms of economics and practicality	7. Economic Considerations 8. Case Studies: Practical Applications 9. Summary and Conclusions

Figure 1.2 Research methodology.

lighting roadway lighting, surface mine illumination, sports lighting, and the fundamentals of visibility.

Results of construction site visits and reviews of manufacturers' literature were incorporated into the study to ensure practicality and facilitate implementation of the proposed guidelines.

Phase II--Analysis and Development

Using the information collected in Phase I, computer models of the lighting configurations for several typical job sites were generated using a commercially available lighting design software, Advanced Graphical Interface (AGI) for Lighting, produced by Lighting Analysts. These models provided a basis for comparison and helped develop an understanding of the critical relationships which were then utilized in the selection of an appropriate design procedure.

Phase III--Implementation

This phase of the research identified key functions necessary to ensure the continued effectiveness and safety of the lighting system after it is placed in operation.

Phase IV--Evaluation

Testing to ensure the accuracy of the design procedure and confirm that the objectives of simplicity and practicality were achieved were the objectives of the final phase. This was accomplished using computer simulation. Economic impact on project costs was also addressed in this phase.

Summary

This research deals with the development of a guideline, easily utilized by field personnel to determine appropriate light sources and configurations for construction work zones. Provision of quality construction work zone lighting results in improved productivity, enhanced safety, and better quality work. As more and more construction work is performed in the nighttime hours, it becomes imperative that illumination standards be established and reasonable means of attaining these standards be developed.

CHAPTER 2
VISIBILITY REQUIREMENTS

Introduction

Principal research findings presented in the following sections correspond to the first objective outlined in Chapter 1. Initial research was directed at acquisition of information developed by other researchers to ensure a comprehensive understanding of the theoretical aspects of the illumination problem and highlight some basic interactions between light and vision.

Vision depends on light, and the primary goal of any lighting design is to provide an environment in which people, through their sense of vision, can function effectively, efficiently, and comfortably. In the case of the highway construction work zone, visual performance considerations should not only be limited to the construction workers but also include quality assurance personnel and passing motorists. Unless adequate care is taken, a suitable lighting situation might exist for one group yet pose serious hazards for another. Ideal lighting systems strike a balance among all groups involved or affected by the construction process.

With respect to visual performance, the literature falls into three basic areas: visual task, lighting conditions, and human factors. These areas are traditionally considered as primary factors in visual acuity. Table 2.1 summarizes variables affecting each of these components. It should be noted that although the variables are very often discussed individually, a large number of interrelationships exist.

Table 2.1

Primary Factors in Visual Acuity

Visual Task	Lighting Condition	Human Factors
Size	Illumination	Condition of the eyes
Luminance	Glare	Adaptation level
Contrast	Uniformity	Fatigue level
Exposure time		Subjective impressions
Type of object		
Degree of accuracy required		
Task motion		
Peripheral patterns		

The Visual Task

In analyzing the visual task, the most important influencing variables are luminance of the object, luminance of the background, contrast, size, and duration. These variables are all quantifiable and have found application in analytic models.

Luminance is often referred to as photometric brightness and is by definition the luminous flux (light) being emitted, transmitted, or reflected from a surface. It depends both upon the intensity of the light striking an object and the proportion of that light reflected in the direction of the eye.

Visual perception tends to improve with apparent size of the visual task, its contrast to background, and average luminance level of the visual field. In practice, the only factor that can be controlled is luminance. In any particular situation, average luminance is dependent on the lighting system employed.

Historically, researchers have studied one variable at a time. Studies have been conducted to determine lowest threshold contrast (Rea, 1981) or determine smallest size (Lythgoe, 1932) that can be seen at different adaptation levels. It is only recently that researchers have started a systematic study of both size and contrast together (McCann & Hall, 1980). Many of these studies concentrated on threshold responses and have little practical application.

Weston's (1935) work established a trend of diminishing returns. He showed that as background luminance increased, performance as measured by speed and accuracy increased at a lower and lower rate until a point was reached where large changes in the background luminance resulted in only small changes in performance as shown in three cases with varying target size of Figure 2.1. Other researchers have conducted studies on more realistic tasks. During the period 1978 to 1987, Smith and Rea performed several studies relating to common office tasks such as proof reading and check value verification under different levels of illumination. Their findings were consistent with those of Weston. Smith (1978) also addressed the concern that at "very high" levels of illumination a reversal might occur and performance deteriorate. His evidence showed continued, though asymptotic, improvement and no reversal. The work of these researchers suggests that optimal levels of illumination exist in a sense that there is no consequential value added by excessive illumination of a work area.

The duration variable is related to the time it takes for the human eye to register a meaningful visual image. Given enough time, fine detail can be distinguished in poor light. The principle of diminishing returns is also evident with this variable.

Blackwell (1970) developed procedures and instruments for visual task evaluation based on luminance and duration of exposure. His approach involves comparing real world tasks to a standard visibility reference task. Theoretically, the optimal lighting design should be based on luminance of the specific task or tasks.

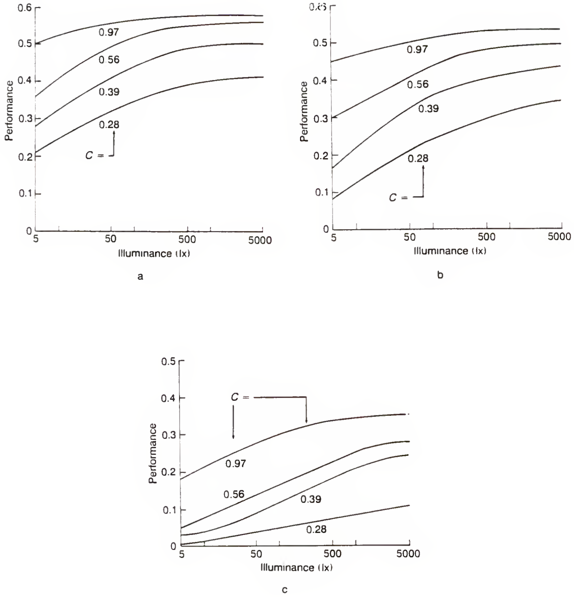


Figure 2.1 Performance as a function of illuminance, target size, and task contrast C in Weston's research. (a) Nominal apparent size = 4.5 min., b) Nominal apparent size = 3.0 min., (c) Nominal apparent size = 1.5 min (IES, 1993).

Blackwell's visibility metric was used by Mayton (1991) to investigate task illumination for surface coal mining equipment operators. Visual tasks were identified for 57 pieces of surface mining equipment including trucks, bulldozers, loaders, graders, and scrapers. Luminance-based visibility measurements in the field were transformed into levels of illumination providing a relative indication of the illuminance levels needed by operators in carrying out various visual tasks. Table 2.2 includes computed values of luminance and illuminance for operators of coal mine bulldozers and graders. These values should provide some insight about the illumination needs of construction equipment operators.

This work can be summarized by noting that, in general, tasks showing high contrast between the task target or critical detail and its background will result in good visibility with relatively lower illumination levels. The opposite also being true, low contrast resulted in low visibility and higher levels of required illuminance.

Lighting Conditions

Sometimes referred to as quantity and quality of lighting, this factor is the most crucial element of this particular research. Influencing variables are illuminance, veiling luminance (disability glare), discomfort glare, luminance ratios, brightness patterns, and chromaticity.

Table 2.2

Illumination Values Resulting from Task Visibility Measurements for Coal Mine Bulldozers and Graders (Mayton, 1991)

	Existing illuminance (lx)	Viewing distance (m)	Computed luminance (cd/m^2)		Reflectance (percent)	Computed illuminance (lx)	
			20 to 30 yr olds	40 to 60 yr olds		20 to 30 yr olds	40 to 60 yr olds
Bulldozer tasks							
Dirt at right blade end	16.8	6.1	0.22	0.36	1.9	35.1	58.4
Top edge of blade against load pushed	459	4.3	1.4	3.0	5.0	90.7	186
Left blade end against load pushed	9.3	4.6	1.1	2.2	30.2	11.6	22.7
Left blade end pushing against muddy load	16.3	5.3	0.12	0.19	4.6	8.2	12.9
Grader tasks							
Pothole in road	3.3	25.9	8.8	28.9	29.0	95.1	313
Top of window at right blade end	11.2	4.5	0.36	0.63	4.81	23.7	41.1
Top of left blade end	67.4	3.3	0.05	0.07	1.0	15.7	23.2
Rock on road	4.7	19.8	1.7	3.5	22.7	23.2	48.7
Clumped dirt at right blade end	14.5	4.5	18.5	88.3	28.2	207	985

Quantity of lighting refers to illuminance, the illuminous flux density measured in lumens per square meter (lux) or square foot (footcandles). Usually, illuminance is given in the horizontal plane; however, it can also be measured in the vertical plane.

Quality of lighting relates to the relative ability of available light to provide the contrast differences so that people can make quick, accurate, and comfortable recognition of cues required for the seeing task. Variables most often associated with quality are glare, uniformity, and chromaticity. It should be recognized that, in many instances, changes intended to optimize one variable will adversely affect another, and the resultant total quality of the configuration may be degraded. A good lighting layout is the result of compromise among variables.

By definition, glare is the sensation of discomfort and interference with vision produced by visual field luminance sufficiently greater than that to which eyes are adapted. It arises because of an unsuitable luminance distribution or extreme luminance contrasts in space or time. Two types of glare are discussed in the literature, disability glare and discomfort glare.

Disability glare is more accurately called veiling luminance in recent literature and is most commonly thought of as coming from discrete sources of glare on or near lines of sight such as automobile headlamps. It is an actual measurable reduction in contrast resulting from intraocular light scattering. Light intended for the primary retinal image is scattered to adjacent retinal areas while light intended for adjacent areas is scattered onto the primary image. Every luminous point in space acts as a source of stray light for nearby points and reduces their contrast.

Causes of disability glare are well understood, which is not so for discomfort glare. It is recognized purely as a sensation of discomfort with no quantifiable impingement on the ability to see. Laboratory studies by Fry and King (1975) have related discomfort glare to pupillary activity, but insufficient data exist to apply their findings to engineering practice. Most analyses of discomfort glare are based on size, luminance, and number of glare sources; their location in the field of view; and background luminance. Guth (1963) developed procedures for multiple sources and suggests development of standardized procedures for preparation of discomfort glare tables.

The borderline between comfort and discomfort (BCD) is a useful measure defined as the luminance L_b just necessary to cause discomfort (Luckiesh & Guth, 1949). This threshold criterion is described by the function

$$L_b = cF^{0.44}$$

where

F = adaptation luminance (background)

c = 302 for interior spaces (Luckiesh & Guth, 1949)

= 529 for night driving (Putmann & Faucett, 1951)

and shown graphically in Figures 2.2 and 2.3.

Effect of glare source size on BCD luminance is shown in Figure 2.4 and 2.5. Moving the glare source away from primary lines of sight results in BCD curves as shown in Figure 2.6.

There are currently studies underway to ascertain relative comfort-discomfort of roadway lighting systems. No results are available at this time.

Uniformity is a measure of relationships of illuminance over an area such as brightness ratios and patterns of luminance. Poor uniformity may distort visual perception of the work zone. Many methods are available to express uniformity including

1. Coefficient of variances (CV)
2. Uniformity gradients (UG)
3. Maximum to minimum illuminance (M/M)
4. Maximum to average illuminance
5. Average to minimum illuminance
6. Minimum to target illuminance

For industrial lighting uniformity is typically expressed as the ratio of the average illuminance to the minimum illuminance over the relevant area. Contrast is desired in

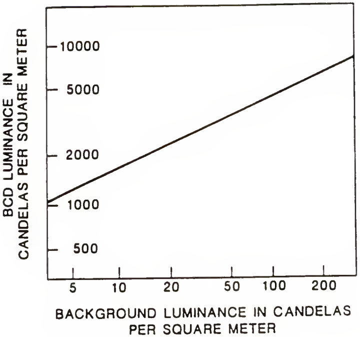


Figure 2.2 The luminance of a glare source at discomfort threshold (BCD) as a function of moderate background luminance (IES, 1993).

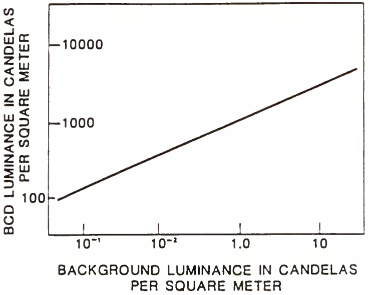


Figure 2.3 The luminance of a glare source at discomfort threshold (BCD) as a function of low background luminance (IES, 1993).

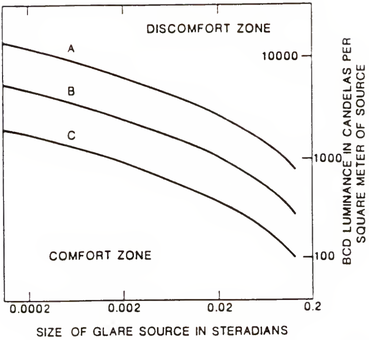


Figure 2.4 The effect of glare source size on the BCD at three moderate levels of background luminance (IES, 1993).

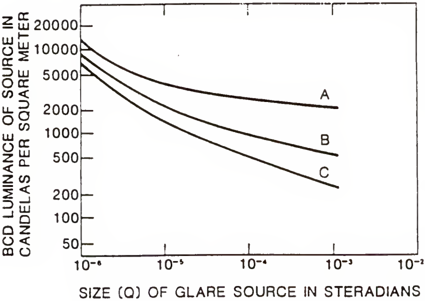


Figure 2.5 The effect of glare source size on the BCD at three low levels of background luminance (IES, 1993).

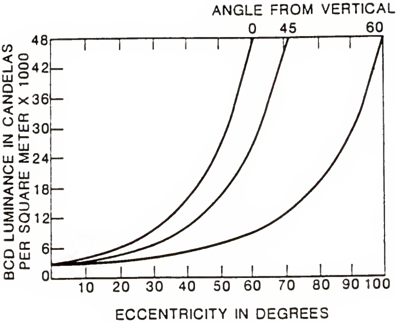


Figure 2.6 BCD luminance for glare sources at various angular distances from the line of sight along several meridians (IES, 1993).

the object of view but undesirable in the field of view. Degree of uniformity required depends on the type of installation. Acceptable values range from 10:1 to 2:1, with 5:1 generally considered suitable for construction activities. Uniformity depends on luminous intensity distribution, spacing/mounting height ratio, and direction of the luminaires beams.

Since brightness attracts the eye's attention, all individual sources in the field of view produce an overall impression. If there is a lack of harmony or order among sources, the overall impression can be annoying to observers. Visual clutter is referred to as "noise." Excessive "noise" results in losses in productivity due to fatigue. Positioning of light sources is, therefore, very important.

Chromaticity refers to the color temperature of a light source or its appearance. Although measured in degrees Kelvin, correlated color temperature of a light source is an indication of color of light produced and not of actual source temperature.

Recent work at Lawrence Berkeley Laboratory has raised a challenge to many of the traditional beliefs about lumens, vision, and lamp efficacy (Benya, 1990). Previous research by IES and CIE has resulted in standardized curves as shown in Figure 2.7 that simply say the human eye is most sensitive around wavelengths of 550 nanometers. This corresponds to the yellow-green portion of the light spectrum. The Berkeley

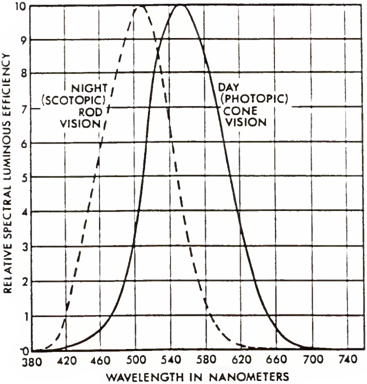


Figure 2.7 The relative spectral sensitivity for photopic (cone) and scotopic (rod) vision (IES, 1993).

research suggests that blue rich sources reduce focusing problems so common when viewing tasks at multiple distances while achieving the greatest visual sensitivity. Establishment of a new light measure, corrected for scotopic eye functions, is suggested. Table 2.3 summarizes their findings and shows conversion factors for converting lumens to "pupil lumens." Based on these light source efficacies, metal halide and fluorescent sources appear to have great potential.

Human Factors

Issues of the illumination problem introduced by human factors, both physical and psychological, are most complex. On the physical side, primary variables are condition of eyes, adaptation level, and fatigue level, all of which are extremely difficult to quantify.

Any condition, either physical or physiological, that handicaps the fovea will adversely affect the eyes ability to accommodate changes in visual target distance. This accommodative function is known to decrease rapidly with age such that by age 60 there is very little accommodative ability. There is also a marked reduction in the wavelengths transmitted by the optics of the eye as one ages. For young eyes, approximately 70% to 85% of the visible spectrum reaches the retina (Said & Weale, 1959). As the eye lens thickens and yellows with age, there is a reduction in

Table 2.3

Various "Pupil" (Scotopic) Efficacies of Common Lamps (Benya, 1991)

Source	Lumens/ watt	Correction factor	Pupil-lumens/watt
Std incandescent	17	1.40	24
Tungsten halogen	22	1.50	33
2900K WW fluorescent*	65	.97	63
2850K WWDX fluorescent*	48	1.14	55
3500 K triphosphor fluorescent (thick coat)*	69	1.37	95
5000K, 90 CRI fluorescent (C-50)*	46	2.19	101
Vitalite fluorescent*	46	2.21	102
5000K pure triphosphor fluorescent*	70	1.96	137
Daylight fluorescent*	55	2.22	122
Deluxe mercury vapor	40	0.80	32
35-watt high pressure sodium	55	0.44	24
50-watt high pressure sodium	65	0.62	40
Low pressure sodium	110	0.24	26

Preliminary values from Lawrence Berkeley Laboratories research.
*Fluorescent efficacies based on 2 40-watt lamps operated on an energy-saving magnetic ballast.

short-wavelength transmittance of up to four times accompanied by a general reduction at all wavelengths (Coren & Girgus, 1972). Both types of loss described above can be somewhat compensated for with increased illumination.

Adaptation refers to the ability of the visual system to change its sensitivity to light. It involves four processes of which transient adaptation is of particular interest. Transient adaptation is the phenomenon of reduced visibility after viewing a higher or lower luminance than that of the task. In a construction work zone this could be related to an equipment operator whose scan might move from well-illuminated nearby tasks to more distant tasks that have little or no lighting. Rinalducci and Beare (1974) concluded that at low illuminance levels sudden increases produced greater losses in visibility than downward changes. Maintaining maximum uniformity will minimize the effects of transient adaptation. It also suggests that the existing illumination in areas adjacent to the work zone needs to be considered when optimizing the lighting environment. A recent study (Hostetter et al., 1993) concluded that as motorists passed from dark areas to an illuminated area, the detection distance for a small target was significantly shorter than in the darkened areas. Although the study is consistent with the findings of Rinalducci and Beare and attributes this loss in visual performance to the phenomena of transient adaptation, a careful analysis of the experimental procedure suggests that it could also be attributed to glare. The fact remains, however, that visual performance of motorists can be measurably impaired by work zone lights.

There is growing evidence that perceived quality of lighting systems relates to more than task visibility. Subjective impressions or psychological reactions have been evaluated with respect to illuminance, spatial distribution, and color.

A general trend replicated in numerous studies is for increased satisfaction with higher illuminance, followed by a decrease in satisfaction at the highest illuminance. Table 2.4 provides ranges of preferred illuminance from several studies. The large range in illuminance is accounted for by differences in age of the observers and visual tasks being performed.

Results of studies into psychological effects of different spatial distributions, or uniformity, are included as Table 2.5. They suggest some consensus with respect to ratios for task and immediate surroundings, however, less agreement for more remote surfaces.

Historically, color appearance of light has been treated in a psychological context. Low color temperatures at high levels of illumination create a very artificial and overly colorful environment while high color temperatures at low illuminance make the environment appear cold and dim.

Table 2.4

Preferred Light Levels (IES, 1993)

	Preferred Average Light Level at Working Plane	
Experimenter	Illuminance (lux)	Luminance (cd/m^2)
Balder, 1957		130
Bodmann, 1962-7	700-3000	90-380
Saunders, 1969	800-1000	
Bean & Hopkins, 1980	>200	
Namecek & Grandjean, 1973	400-850	

Table 2.5

Preferred Luminance Ratios (IES, 1993)

	Area					
Experimenter	Immediate Surround	Front Wall	Rear Wall	Right Wall	Left Wall	Ceiling
Touw, 1951	.3					
Bean & Hopkins, 1980	1					
Tregenza et al., 1974		.52	.64	.51	.55	.85
van Ooyen et al., 1987	.4		.3	(All Walls)		
Roll & Hentschell, 1987	.1-.6					.1-3

Note: All entries are relative to the task background luminance.

Figure 2.8 illustrates the preferred combinations of illuminance and color temperature. This effect was originally presented by Kruithoff (1941) and subsequently confirmed by Baron, Rea, and Daniels (1992).

As mentioned previously, the subjective nature of the research has made it difficult to draw conclusions in many cases. This is clearly illustrated by Figure 2.9 which is an indication of the percentage of observers rating a given luminance as too dark, good, or too bright. Note the lack of agreement across the entire range evaluated.

Summary

There are many complex and interrelated factors contributing to the lighting environment. However, only a few of them are within the control of the lighting designer. The visual task is fixed by the nature of the construction, and most of the variables relating to human factors are not controllable due to the diversity of the population that will be affected. The primary influence is within the variables of the lighting condition.

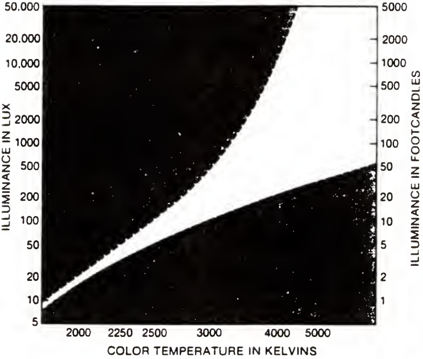


Figure 2.8 Preferred color temperatures (the unshaded area) at various illuminance levels (IES, 1993).

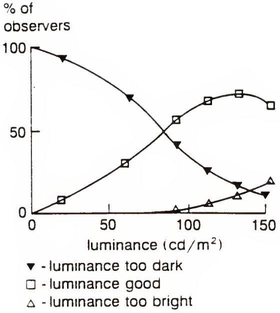


Figure 2.9 Percentages of observers rating a luminance as too dark, good, or too bright (IES, 1993).

CHAPTER 3
SELECTING LIGHTING EQUIPMENT

Introduction

Proper selection of lighting equipment along with its correct application is essential if a lighting system is to serve its intended purpose efficiently and economically. Knowledge of fundamental characteristics of lighting equipment and familiarity with current hardware and developments within the industry is one of the first steps toward an effective lighting system. Prior to designing a lighting system, lighting equipment manufacturers or their product line representatives should be contacted to obtain current product information. Lighting manufacturers shown in Appendix A were contacted to survey their specific experiences with construction work zone lighting. Although many responses were received, most only provided photometric data and were unable to contribute any construction related experiences.

This chapter describes major components of a lighting system and introduces how system performance is described in photometric test reports. For purposes of clarity it has been divided into three basic elements:

1. Light Sources
2. Luminaires
3. Photometric Data

Light Sources

Review of relevant lamp types and their main characteristics is the purpose of this section. The most important element of illumination systems is the light source. It is the principal determinant of visual quality, economy, and efficiency.

Two basic types of light sources are commonly used for construction work zone lighting: incandescent and high intensity discharge (HID). Each light source type has inherent advantages and disadvantages. A summary of important lamp characteristics is provided as Table 3.1 while Table 3.2 provides recommendations for applications.

Incandescent Lamps

Incandescent lamps include general service lamps and tungsten halogen lamps as shown in Figure 3.1 and 3.2. Their chief advantages are low initial cost, good color rendering, and good optical control capabilities. Low efficacy and short life of these lamps are their primary disadvantages. However, as temporary or portable lighting they are considered quite useful. Their instant start ability is also important for construction applications. A major concern

Table 3.1

Important Lamp Characteristics (IES, 1993)

Light Source	Lumen Output per Lamp	Efficacy (Lumens per watt)	Life (hrs)	Color Adaptability	Degree of Light Control	Maintenance of Lumen Output
Incandescent-Tungsten Halogen	Fair	Low (24)	Low (2,000)	High (Day Light White)	High	Fair
Mercury Vapor	Good	Fair (63)	High (24,000)	Fair to Good (Medium White)	Fair	Fair
Metal Halide	High	Good (110)	Good (10,000)	Good (Bright White)	Good	Good
High Pressure Sodium	High	High (140)	High (24,000)	Fair (Soft, Orange)	Good	High
Fluorescent	Low	Fair to Good (85)	Fair (7,500)	Fair to High (Daylight White)	Fair	High

Table 3.2

Lamp Applications

Light Source	Recommended Applications
Incandescent Tungsten Halogen	Task-oriented lighting Equipment mounted lights Small areas Low mounting heights
Mercury Vapor	Not recommended
Metal Halide	Medium sized areas Good color rendition required Varied mounting heights
High Pressure Sodium	Large areas Color rendition not important Varied mounting heights
Fluorescent	Not recommended

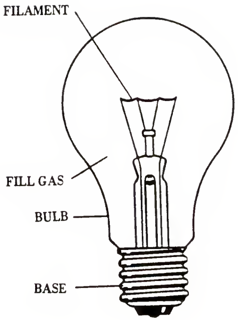


Figure 3.1 Typical incandescent lamp (IES, 1993).

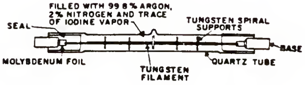


Figure 3.2 Typical tungsten-halogen lamp (IES, 1993).

when mounted on construction equipment would be their sensitivity to vibration. Incandescent lamps are normally made smaller for vibration service (up to 150 watts) and for rough service (up to 500 watts).

Discharge Lamps

The electric discharge family includes metal halide, mercury, high pressure sodium, low pressure sodium, and fluorescent lamps. Typical metal halide and mercury lamps are shown in Figure 3.3 and high pressure sodium in Figure 3.4. In general, they all have long lamp life and improved luminous efficiency. There is a time delay and slow buildup of light output when the lamps are first energized or after restart. A properly designed discharge system typically requires fewer luminaires than an incandescent system. However, it does require a current limiting device, called a ballast, that is not necessary with incandescent systems. High intensity discharge lamps are less fragile than most incandescent lamps and will stand up to more vibration. The lumen output of metal halide lamps is sensitive to operating position of the lamp. The highest output is obtained with the lamp operating in the vertical position. The lowest output is usually obtained with the lamp tilted 60 to 75 degrees off vertical. Manufacturers data usually include a derating factor for tilted operation.

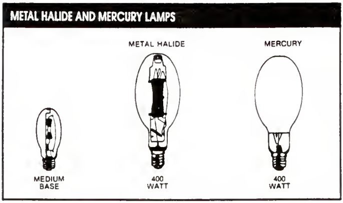


Figure 3.3 Typical metal halide and mercury lamps (GE, 1992).

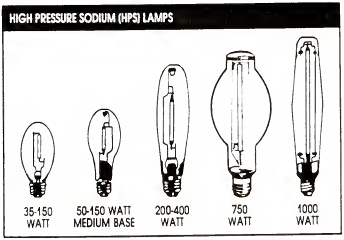


Figure 3.4 Typical high pressure sodium lamp (GE, 1992).

Luminaires

Photometric characteristics are largely determined by the luminaire. It is composed of one or more lamps together with parts designed to distribute light, to position and protect lamps, and to connect lamps to the power supply. One of the first steps in glare control is in selection of a luminaire with proper distribution characteristics or shielding. Luminaires can also serve as shock absorbers to minimize effects of vibration. Figure 3.5 illustrates several typical luminaires used for floodlighting including round spun and cast heavy duty with vertical and horizontal lamps.

Floodlights are classified into three categories: enclosed heavy duty (HD), enclosed general purpose (GP), and sharp cut off. The type typically found on portable light trailers is a GP. A cutoff luminaire is usually designed to shield the light source at angles at some angle, usually above 72 degrees from vertical. Their main advantage is in light control and glare control. Cutoff luminaires generate very distinct light patterns. Knowledge of a particular pattern is useful for preliminary design selections. Detailed design can be accomplished with photometric data provided by manufacturers of specific luminaires to be used.

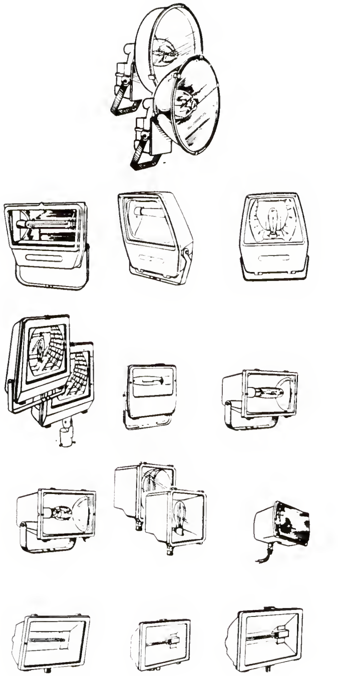


Figure 3.5 Typical floodlighting luminaires (GE, 1992).

Photometric Data

Photometric data are used to accurately describe performance of luminaires in terms of light distribution. Characteristics such as candlepower distribution, zonal lumens, efficiency, luminance, beam widths, and typing are provided for use in design, specification, and selection of lighting equipment. Data are typically provided in either tabular or graphical formats.

Understanding presentation of horizontal and vertical angles is required for comprehension of the luminaire light distribution. Horizontal angle ranges describe the level of symmetry that a light distribution possesses as shown in Figure 3.6, while the range of vertical angles indicates distribution of light in an upward or downward direction.

Horizontal angles are described as if the luminaire is viewed from above and angles measured in a counterclockwise fashion as illustrated in the plan view of Figure 3.7(a). Within each horizontal plane there is a series of vertical angles. At each of these vertical positions light intensity is measured beginning directly below the luminaire at the photometric nadir as shown in Figure 3.7(b). Viewing light intensity at each vertical angle within a single horizontal angle results in a curve similar to the one shown in Figure 3.7(c) for the 45-degree horizontal plane depicted in Figure 3.7(a).

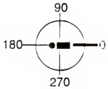
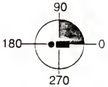
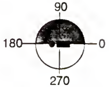
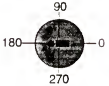
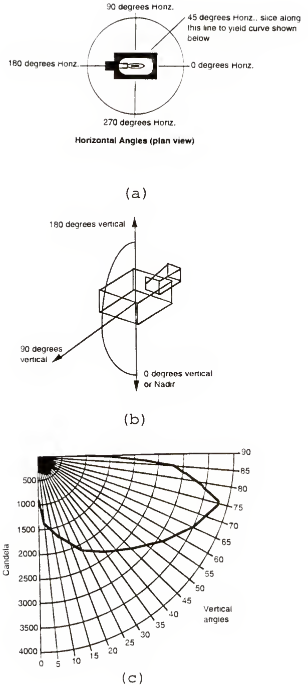
Implied Symmetry	**Range of Horizontal angles reported**	**Illustration (plan view)**
Symmetric	0 (zero, only 1 angle required)	
Quadrilateral Symmetry	0 - 90 degrees (usually 5 angles or more)	
Bilateral Symmetry	0 - 180 degrees (usually more than 9 angles)	
No Symmetry (asymmetric)	0 - 360 degrees	

Figure 3.6 Implied symmetry for standard photometric reporting schemes (Lighting Analysts, 1993).



(a)

(b)

(c)

Figure 3.7 Presentation of angles in photometric data (a) Horizontal angles, (b) Vertical angles, (c) Elevation view of the 45 degree horizontal plane of candela (Lighting Analysts, 1993).

The IES has developed a standard format tabular report that summarizes essential data. An example of this report is shown as Figure 3.8. Often data are used to represent an entire family of lamps having the same light center. In this case, the report's lumen basis is established as 1000 or some multiple thereof, and tabulated data can be adjusted for specific lamp lumens by multiplying each point by the ratio of actual lamp rated lumens to the report lumen basis. Candela distributions can also be presented graphically. Figure 3.9 is a useful curve based on the primary axis. Isofootcandle charts are useful in determining direct components of illuminance for a particular luminaire. Figure 3.10 illustrates charts used for horizontal surfaces and vertical surfaces and fixed mounting heights.

Summary

Selection of lighting equipment is complicated by the wide variety of sources and luminaires available. There is no one best solution for a given application. With performance requirements in mind, characteristics of the luminaire should be reviewed and those that are unsuitable eliminated. Accurate engineering and design of the overall illumination system is dependent upon the availability and use of current photometric data.

```
IESNA91
(TEST) 12345
(MANUFAC) Generic Lighting Company
(LUMINAIRE) Super-optic 10
(LAMP) 150 watt HPS
TILT = NONE
LAMPS = 1  LUMENS/LAMP = 16000          PHOTOMETRIC TYPE = 1  WATTS = 185
LUMINOUS DIMENSIONS (FEET): WIDTH = 1    LENGTH = 1   HEIGHT = 0   FACTORS:
MULTIPLIER = 1      BALLAST = 1      BALLAST-LAMP = 1
NUMBER OF VERTICAL ANGLES = 11 : 0 TO 90 DEGREES
NUMBER OF HORIZONTAL ANGLES = 5 : 0 TO 90 DEGREES

HORIZONTAL ANGLES ACROSS TOP

            0           22.5         45           67.5         90
            ____        ____         ____         ____         ____

0           900         900          900          900          900
5           1200        1300         1400         1300         1200
15          1500        1600         1700         1600         1500
25          1800        1900         2100         1900         1800
35          2100        2200         2400         2200         2100
45          2400        2500         2700         2500         2400
55          2700        2800         3100         2800         2700
65          3100        3100         3500         3100         3100
75          2700        3400         3800         3400         2700
85          2000        2500         2800         2500         2000
90          1000        1000         1000         1000         1000
```

Figure 3.8 IES format photometric report (Lighting Analysts, 1993).

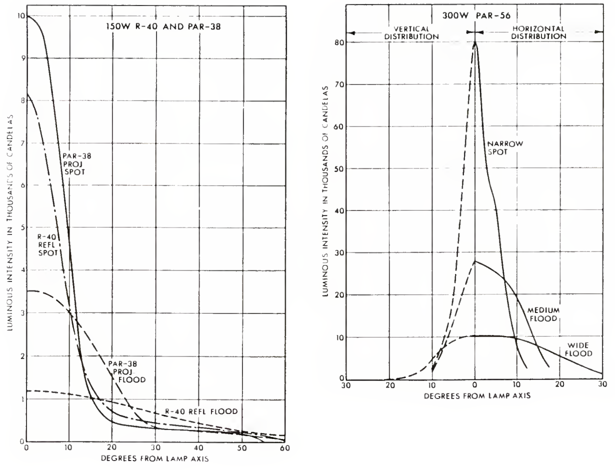


Figure 3.9 Candela distribution curves (IES, 1993).

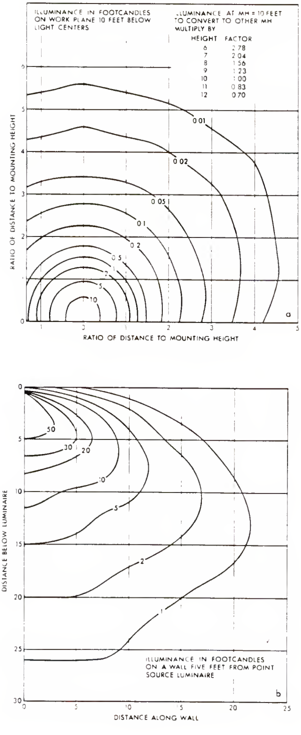


Figure 3.10 Isofootcandle charts (IES, 1993).

CHAPTER 4
CONFIGURATION OF THE LIGHTING SYSTEM

Introduction

An important consideration prior to actual selection of lighting equipment is the desired system configuration. Factors affecting this decision include work zone size, required mobility, duration of work, required illuminance levels, and cost. The discussion in this chapter corresponds to objectives two and three as stated in Chapter 1, that is, to review current nighttime construction practices and assess capabilities of available light sources in a construction environment.

Given previously mentioned factors, there are three basic options for configuring illumination systems: temporary, portable, or equipment-mounted. Advantages and disadvantages for each option will be discussed after the work zone has been further defined.

Work Zone Description

Typical highway construction work zones are linear in nature. Linearity refers not to the physical length of the work zone but rather to the flow of the construction activity within the work zone. One operation or crew follows another sequentially. Highway construction involves activities such as clearing, grubbing, grading, subbase, base course, and paving. Each of these activities is usually repeated by the same crew from one end of the project to the other with the only distinguishing feature being rate of progress. A 1978 study involving construction zones characterized typical work zones as 9.6 km (6 miles) in length and having an average project duration of 230 days (Graham, Paulsen, & Glennon, 1978). Table 4.1 outlines both construction and maintenance activities often performed at night.

Knowing the type of work being performed and the nature of the work zone, it is possible to determine the most suitable lighting system for a specific construction application.

Temporary Systems

A temporary system is defined as a fixed lighting system intended to illuminate an entire work zone or some large portion thereof. It is assumed the luminaires will be mounted either on poles that have been temporarily placed or on existing poles. Initial costs for this type of system include purchasing and installing poles, foundations, mounting hardware, luminaires, and wiring. Costs of energy and removal of poles should also be taken into consideration.

Table 4.1

Highway Construction and Maintenance Activities Performed at Night

Maintenance and Consruction Tasks Performed at Night

- Earthwork/embankment
- Excavation
- Reworking shoulders
- Barrier wall or traffic separator
- Milling and removal
- Concrete pavement
- Resurfacing
- Repair of concrete pavement
- Crack filling
- Subgrade stabilization
- Pot filling
- Base courses
- Surface treatment
- Waterproofing/sealing
- Sidewalks
- Sidewalk repair
- Riprap placement
- Riprap maintenance
- Guardrail, fencing
- Resetting guardrail/fencing
- Painting stripes, pavement markers, metal buttons
- Landscaping
- Highway signing for construction
- Highway signing for maintenance works
- Traffic signals
- Highway lighting system
- Bridge decks
- Drain structures, culverts, and sewers
- Concrete structures
- Sweeping and cleanup

The primary advantage of a temporary system is in the high quality of illumination that can be achieved. Luminaires can be spaced uniformly subject to any work zone physical constraints and at relatively high mounting heights. This serves to provide uniform illumination with minimal glare and eliminates unnecessary equipment from within the work zone.

Disadvantages of temporary lighting are in the cost and potential inefficiency due to illuminating areas of minimal or no activity. There may also be some difficulty associated with assuring adequate power.

A variation of this temporary scheme that merits consideration relies on the use of existing street lighting systems. Most roadway lighting is designed for approximately one or two footcandles of illumination. If adequate power is available, it might be possible to retrofit existing luminaires with higher wattage lamps. This technique requires familiarity with existing hardware and power distribution systems and should only be considered after consulting both the equipment manufacturer and owner of the system.

Portable Systems

An illumination system designed in such a manner that it can be easily moved from one location to another will be classified as a portable system. Figure 4.1 illustrates a

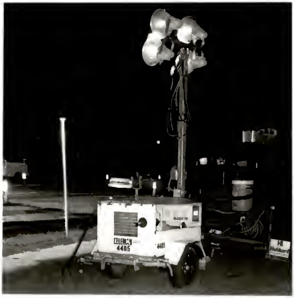


Figure 4.1 Trailer-mounted portable light plant.

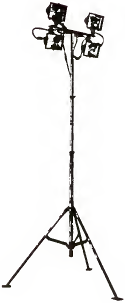


Figure 4.2 Collapsible tripod portable light stand.

trailer-mounted system often found on job sites, and Figure 4.2 shows a collapsible tripod arrangement that is also very popular. A required feature of this type of system is the power supply or generator which eliminates reliance on existing utility service. Commercially available systems have a wide variety of features, such as hydraulic or electric controls, to enhance or simplify their use. Tower heights range from 1.8 meters (6 feet) to a full 9.1 meters (30 feet) and are usually rotatable 360 degrees for easy floodlight aiming.

Luminaires generally provided with portable systems are round spun GP floodlights with a 1000-1500 watt metal halide or high-pressure sodium lamp. Smaller systems are equipped with tungsten halogen floodlights rated at 500-1500 watts.

Advantages of this type of system are that it is self-contained and can be easily moved about the jobsite, thus providing flexibility in the illumination design. Units are available from most construction equipment rental agencies or can be purchased. They are also very reliable and easy to operate and maintain. On the negative side, units available for rental are typically equipped with much more light than would be desired under most circumstances. In addition to not being very cost effective, it has been noted that these units tend to create a tremendous glare hazard on jobsites. Because of the high luminance sources and low mounting heights, extreme care must be taken in the positioning and aiming of these lights.

Equipment-Mounted Systems

A survey of current practice finds frequent reliance on construction equipment-mounted light systems. This raises a question regarding intent and capability of installed lights. Appendix B includes a list of construction equipment manufacturers contacted to discuss this issue. None of the manufacturers provided information that would indicate the factory-integrated lights are actually engineered to provide predetermined task-specific lighting levels. Most responses were in terms of number of lights and locations while a few actually provided recommended lamp wattage.

Discussions with engineers for J.I. Case Company pointed out Society of Automotive Engineering (SAE) criteria as the basis for lighting systems on most construction equipment. SAE standards have been developed to provide specifications for lighting and marking of industrial wheeled equipment whenever such equipment is operating on or travelling on a highway (SAE J99 MAR86). As such, these standards do not actually pertain to work zone lighting. There are, however, SAE-recommended practices suggesting use of particular floodlamps for illumination of work areas close to equipment (SAE J1029 MAR86). These recommendations give no indication of the expected illuminance levels.

A study sponsored by the U.S. Army Corps of Engineers, provides a very detailed discussion of night work lighting systems for construction equipment (Cashell, 1946). Although quite old, recommendations of this study are evident in positioning of lights on current equipment. It should be noted that as with SAE recommendations, this study is without any substantive information with regard to required or desired illumination levels. It was, however, very thorough and took into consideration subjective opinions of experienced equipment operators while forming a consensus standard for mounting of equipment lights. This is not all that different from the process used in development of current illuminance recommendations.

Among other constraints when considering equipment mounted lighting is alternator capacity for the particular piece of equipment. A review of manufacturers' data shows standard equipped alternators ranging from 20 to 75 amps. Assuming approximately 10 amps are required for battery charging and no other significant electrical load, available ampacity for task lighting could range from 10 to 65 amps. Using the relationship

$$\text{Watts} = \text{Volts} \times \text{Amperes}$$

there is a potential to run lights rated from 240 to 1560 watts on a 24 volt system or 120 to 780 watts on a 12 volt system.

Many contractors are mounting portable generators on their construction equipment to operate 120 volt lighting systems. A survey of available generators finds on the low end of the power spectrum, a 350 watt unit with a footprint of 632 square centimeters (98 square inches). On the high end there is a 2500 watt unit with a footprint of 2,129 square centimeters (330 square inches). Portable generators are actually available up to about 6,500 watts; however, with a footprint of 7,884 square centimeters (1,222 square inches), they start to become quite bulky and would not fit on most construction equipment.

One problem reported by Cashell was reduced lamp life when using the 120 volt system. This was attributed to vibrations and was such a problem at the time that using AC generators was discarded as an option. This problem, although still present to a limited extent, is not as severe due to advances in lighting equipment technology. There are light manufacturers specializing in lights for what is characterized as rough or vibration service.

Several advantages were found when comparing equipment mounted lights to area floodlighting. Among them are the following:

1. High intensity illumination on the work plane.
2. Positioning of lights between operator and task eliminates shadows.
3. Operator can adjust light to direct high intensity illumination where needed.
4. Rate of work can approach daytime rate.
5. Equipment can be operated independently of general illumination.
6. Possibility of general shutdown of work due to failure of lighting and power generating equipment is minimized.
7. Minimizes need for equipment such as floodlight trailers and generators thus eliminating time and labor spent in transporting and erecting such equipment.

In the literature provided by construction equipment manufacturers, there is a very noticeable similarity in the positioning of lights for equipment of the same type and different manufacturer. As mentioned previously, these layouts are very similar to those suggested by Cashell and will allow the development of equipment mounted lighting schemes that are rather generalized with respect to equipment type.

Mounting Considerations

Luminaire mounting systems include all of the structural hardware used to hold the luminaire in place. Vertical supports or poles selected will be dependent on specific configurations and could be either metal or wood. It should be capable of supporting the mounted equipment weight including luminaires, brackets, and any crossarms. At the same time it should withstand effects of the maximum velocity winds to which it will be subjected. Using manufacturer's catalog data, appropriate brackets and poles can be selected based on luminaire weight, effective projected area, desired mounting height, and maximum anticipated wind velocity for the geographic area. Wind velocity can often be found in the manufacturer's data or structural design manuals such as ANSI/ASCE 7-88, Minimum Design Loads for Buildings and Other Structures.

Glare Avoidance

Hazards associated with glare have been found to be a serious problem in nighttime highway construction. Glare can cause physical annoyance and discomfort with a resulting loss of visual performance to the highway construction crew and passing motorists, as cited previously in the work of Hostetter et al. (1993). A primary concern in configuration of lighting systems should be reduction of objectionable glare effects to a minimum. This is accomplished through consideration of four factors relating to beam spread, mounting height, location, and aiming as shown in the glare avoidance checklist of Table 4.2.

IES/NEMA beam spreads shown in Figure 4.3 were determined by locating the point away from the beam center where 10% of the maximum candlepower occurs. Floodlight patterns are described about both horizontal and vertical axis and can be categorized as either symmetrical or asymmetrical. Effective projection distances are measured in a straight line from the base of the mounting pole to the area being illuminated. Vertical beam spread is potentially a source of glare and should be selected as narrow as possible for most highway construction applications.

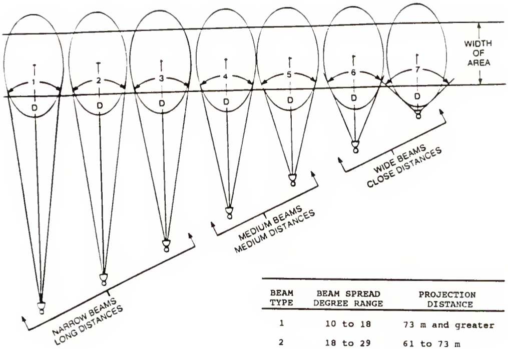
Determination of proper mounting height is also crucial in controlling glare. Mounting luminaires at lower than optimum levels can cause severe problems. In general, mounting height is related to lumen rating of the light source as shown in Figure 4.4. High luminance sources require increased mounting heights.

Minimum glare producing mounting height is based on the tested principle that the angle created by the horizontal working surface and a line drawn through the floodlight and a point one-third the distance across the work zone should not be less than 30 degrees (McGraw-Edison, 1983). By analyzing the geometry, it can be seen that if the light is set back any distance from the work zone, mounting height will

Table 4.2

Glare Avoidance Checklist

Beam Spread	Select vertical and horizontal beam spreads to minimize light spillage.
	Consider using cutoff luminaires.
Mounting Height	Coordinate minimum mounting height with source lumens as shown in Figure 4.4.
	Angle formed by line drawn through luminaire and horizontal working plane at 1/3 the effective distance across the area to be illuminated is greater than 30°.
Location	Luminaire beam axis crosses normal lines of sight between 45° and 90°.
Aiming	Angle between main beam axis and nadir less than 60°.
	Intensity at angles greater than 72° from the vertical less than 20,000 candela.
Supplemental Hardware	Visors
	Louvers
	Shields
	Screens
	Barriers


WIDTH OF AREA
1
2
3
4
5
6
7
D
NARROW BEAMS LONG DISTANCES
MEDIUM BEAMS MEDIUM DISTANCES
WIDE BEAMS CLOSE DISTANCES

BEAM TYPE	BEAM SPREAD DEGREE RANGE	PROJECTION DISTANCE
1	10 to 18	73 m and greater
2	18 to 29	61 to 73 m
3	29 to 46	53 to 61 m
4	46 to 70	44 to 53 m
5	70 to 100	32 to 44 m
6	100 to 130	24 to 32 m
7	130 and up	under 24 m

Figure 4.3 IES/NEMA beam spread classifications and their effective projection distances (IES, 1993).

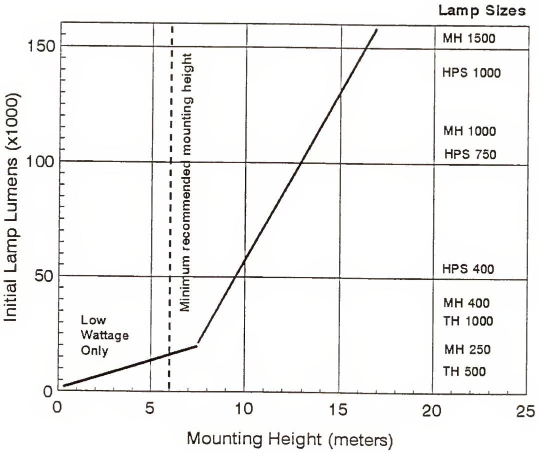


Figure 4.4 Recommended relationship between mounting height and source lumens.

increase dramatically. Typically 6.1 meters (20 feet) is accepted as the minimum mounting height for floodlights or area lights. Task-specific lighting is generally of much lower wattage or luminance and can be mounted at heights appropriate to the task.

Luminaire location or positioning in the horizontal plane can also generate disabling glare. Maximum glare occurs when the viewer must face directly into the luminaire. As the luminaire is viewed from angles away from the beam axis, glare appears to decrease. By removing luminaires away from normal lines of sight of motorists and workers, effects of glare can be diminished. Positioning of luminaires out of normal lines of sight or critical viewing angles of motorists and workers can be accomplished through selection of pole location and actual luminaire aiming. Three factors affect the angle between normal lines of sight and a particular luminaire. These include distance between viewer and luminaire, relative height of luminaire, and aiming angle. If any one factor changes, the others will also change. As a rule of thumb, luminaires should be aimed in such a way that a line from the luminaire beam axis should cross normal lines of sight at angles between 45 and 135 degrees in the horizontal. Angles between 90 and 135 degrees are permissible but need to be evaluated in terms of traffic in the opposite direction. If at all possible this angle should not be less than 45 degrees nor greater than 135 degrees.

Proper aiming of floodlights is the fourth factor to be considered. A general rule for aiming is that angles created by the nadir and the center of the luminaire beam spread should not exceed 60 degrees. Another very important consideration in the control of glare is intensity of light at angles greater than 72 degrees from vertical. Seventy-two degrees was selected since it is generally recognized in the lighting industry that discomfort glare is minimized when light strikes an observers eye at an angle less than 72 degrees (McGraw-Edison, 1983). If maximum candlepower in the upper beam, as shown in Figure 4.5, can be limited to 20,000 candela, discomfort glare can be effectively controlled. SAE J579 provides standards for automotive headlamps. In this case, 20,0000 candela is the maximum permissible in a low beam unit. As a contrast, maximum allowable for a high beam unit is 75,000 candela (SAE, 1993).

At times physical constraints of the work zone may limit location of mounting poles to less than ideal sites. In these situations positioning must be carefully evaluated in terms of vital lines of sight or critical viewing angles. Use of shields, visors, and louvers, as shown in Figure 4.6, can help reduce glare in these circumstances. Disadvantages with this approach are that total projected wind load factor will increase causing additional mounting concerns and useable light emitted from the luminaire is decreased.

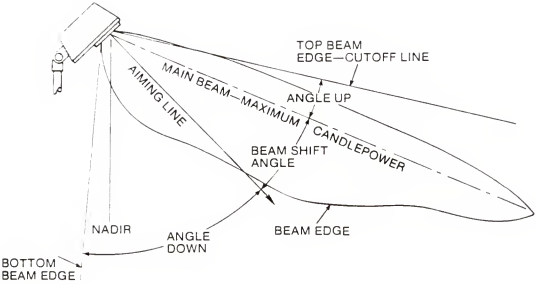


Figure 4.5 Vertical beam components (McGraw-Edison, 1983).

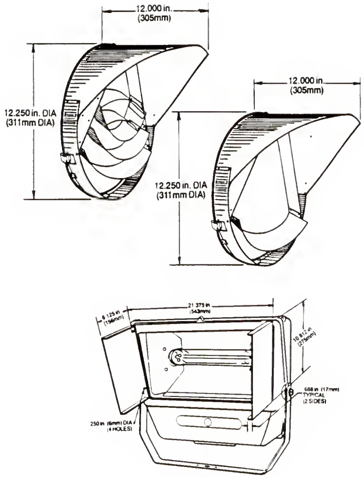

12.000 in. (305mm)
12.250 in. DIA (311mm DIA)
12.000 in. (305mm)
12.250 in. DIA (311mm DIA)
6 125 in (156mm)
21 375 in (543mm)
10 812 in (275mm)
.688 in (17mm) TYPICAL (2 SIDES)
.250 in (6mm) DIA (4 HOLES)

Figure 4.6 Glare shields and louvers (GE, 1992).

Glare avoidance screens or barrier walls are often used as a method to protect workers and motorists. This approach should be considered in any case in which the work zone configuration cannot be managed to avoid glare. Table 4.3 provides a summary of states using screens or barriers to control glare. The height of the screen is an important factor. By increasing height, surface area is also increased and the wind loading will need to be addressed if this option is chosen.

Summary

Work zone lighting systems can be configured several different ways to best meet contract requirements. Options include temporary systems, portable systems, and equipment mounted systems. Temporary systems have potential for high quality light; however, it is usually at higher cost. An equipment-mounted system appears to provide adequate illumination at lowest cost. An ideal solution might be any one or combination of the three options subject to particular constraints of a given project. The selected configuration should be viewed from the perspectives of passing motorists as well as on-site workers. If a glare hazard to either party is detected, consider use of glare avoidance hardware.

Table 4.3

Glare Avoidance Screening Methods Used in Various States

State	Screens or Barriers Utilized to Avoid Glare to Motorists
California	2-foot high plywood "GAWK" screens mounted on concrete barrier walls K-rail used by the contractors for maintenance work.
Georgia	Plywood paddles on concrete barrier walls for apparent glare problem.
Illinois	Screens used usually at crossovers and curves.
Iowa	TBR-mounted glare screens to help separate lanes.
Kansas	Sometimes Jersey barriers are utilized.
Kentucky	Concrete barrier walls.
Maine	Concrete barriers on bridge decks.
Maryland	Modular units consisting of vertical blades mounted on a continuous horizontal base rail.
Missouri	Concrete barrier walls.
Nevada	Vertical panels generally used at curves.
New York	Fabric screens are utilized based on contractor's discretion.
Oklahoma	Median barrier with blade-type portable modular glare screen.
Rhode Island	24 inches high Modular Guidance System on top of Jersey barrier.

CHAPTER 5
DESIGNING THE LIGHTING SYSTEM

Introduction

This chapter corresponds to the fourth objective stated in Chapter 1, development of a robust manual design process based on work zone geometry and light source characteristics that is easy to use. It begins with a discussion of design criteria which are input for the design of a lighting system followed by an explanation of a simplified sequential design process. Procedures are then given for checking the adequacy of the design. Since computer design applications are becoming readily available their use will also be addressed followed by a discussion of techniques incorporated into the design process to minimize any potential problems due to glare.

Design Criteria

Most current lighting design criteria are based to a large extent on IES illuminance recommendations. In 1979, IES adopted the policy of recommending interior illuminance in ranges accompanied by a weighting factor guidance system reflecting lighting performance trends found in research.

The ranges provide a latitude in illuminance selection to account for age of observer, size and contrast of task, and need for speed and accuracy. Ranges were patterned under those in CIE Report No. 29 and were derived on a consensus basis with experience and judgement playing an important role.

Recommended luminance for outdoor activities such as sports and certain industrial operations are provided as a target maintained illuminance. Table 5.1 summarizes IES-recommended illuminance values for construction activities along with luminance or uniformity ratios. Recommended lighting levels provide a guide to efficient visual performance and should not be interpreted as requirements for minimum illuminance levels. Minimum required illuminance levels shown in Table 5.2 have been established with safety as a primary consideration. Influencing factors are inherent risk or hazards requiring detection and level of activity.

Table 5.1

IES Recommended Values (IES, 1993)

Area/Activity	Lux	Footcandles	Luminance Ratios
General construction	100	10	5:1
Excavation work	20	2	5:1

Table 5.2

IES Recommended Minimum Values (IES, 1993)

Hazards Requiring Visual Detection	Slight		High	
Normal Activity Level	Low	High	Low	High
Illuminance Levels				
Lux	5.4	11	22	54
Footcandles	0.5	1	2	5

Additional guidance for selection of illuminance levels can be found in CIE Publication No. 68, Guide to the Lighting of Exterior Working Areas (1986). These recommendations provide somewhat more detail than those of IES and also include suggested uniformity ratios as shown in Table 5.3.

The IES recommendations are approved as American National Standards by the ANSI Board of Standards when substantial consensus has been reached by directly and materially affected interests. Two ANSI standards have relevance to construction work zone lighting. RP-7-91, Industrial Lighting, relates to industrial activities both indoor and outdoor. Required illuminance are in complete agreement with IES recommendations. RP-8, Roadway Lighting, is also very helpful in this analysis due not only to the linearity of the highway construction process but also to the effect on adjacent traffic that must be taken into

Table 5.3

CIE Recommended Values (CIE, 1986)

Visual task	Maintained average horizontal illuminance E_{av} (lux)	Uniformity E_{min}/E_{av} ratio
Operations performed and areas to be lighted		
Movements of people, machines and vehicles, walkways and access routes	20	0.25
Loading and unloading areas, handling of materials	20	0.4
General rough work, site clearance, excavation and soil work	20	0.25
Reinforcing, concreting, shuttering, erection; brick laying (except facings); blockwork; carpentry	100	0.4
Scaffold erection and dismantling steel structural work	100	0.3
Operating circular saws	300	0.4
Stores and stockyards	20	0.25
Security.	Refer to chapter 11	
Site huts (rest rooms, locker rooms, toilets). Site offices (on desks and reference tables, general lighting of drawing offices)	Refer to indoor lighting specifications	

consideration. A third reference, although not distributed as standard practice, is RP-6-88, Recommended Practice for Sports and Recreational Area Lighting. It deals primarily with floodlighting.

The American National Standard is incorporated into law by the Code of Federal Regulations. The OSHA Safety and Health Standards, 29CFR 1926/1910 (1990), provide minimum illumination intensities for construction areas as shown in Table 5.4.

Requirements for a contractor to comply with certain standards are most often conveyed through contract documents such as specifications. A typical clause used by the Florida Department of Transportation (1991) follows:

> In all areas where work is being performed during the hours of dusk or darkness, the Contractor shall furnish, place and maintain lighting facilities capable of providing light of sufficient intensity (five foot-candles minimum) to permit good workmanship and proper inspection at all times. The lighting shall be arranged so as not to interfere with or impede traffic approaching the work site(s) from either direction nor produce undue glare to property owners and travelling public. (p. 62)

This is in contrast to a much more rigorous clause used by the Virginia Department of Transportation (Federal Highway, 1985):

> When night work is in progress, the contractor shall provide sufficient lighting of the work site(s) to enable the satisfactory completion of the work. Lighting shall be arranged so as not to interfere or impede with traffic approaching the site from either direction. Lighting arrangements at the work site(s) shall provide a minimum of 50 footcandles of light for areas of approximately 15 feet by 15 feet with a minimum

Table 5.4

OSHA Required Values (CFR, 1990)

Lux (fc)	Area of Operation
50 (5)	General construction area lighting.
30 (3)	General construction areas, concrete placement, excavation and waste areas, accessways, active storage areas, loading platforms, refueling, and field maintenance areas.
50 (5)	Indoors: warehouses, corridors, hallways, and exitways.
50 (5)	Tunnels, shafts, and general underground work areas: (Exception: minimum of 10 footcandles is required at tunnel and shaft heading during drilling, mucking, and scaling. Bureau of Mines approved cap lights shall be acceptable for use in the tunnel heading.)
100 (10)	General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active storerooms, barracks or living quarters, locker or dressing rooms, mess halls, and indoor toilets and workrooms).
300 (30)	First aid stations, infirmaries, and offices.

> of 5 footcandle in the corners of the area. Lighting shall be from a minimum of 2 fixtures with back-up fixtures and power source readily available. (p. 152)

Another type of standard requiring compliance arises due to local ordinances. Problems of light trespass have been given increasing attention and a number of ordinances are in effect or proposed (Lewin, 1992). The intent of ordinances is to reduce light spillage, restrict illuminance levels, and reduce glare. These constraints are sometimes in conflict with specifications and need to be considered in the lighting design.

All referenced standards have been based on horizontal illuminance. It is well known and accepted that task luminance and glare criteria provide a better correlation with visual impression of lighting quality. It is also recognized that illuminance criteria do not comprise a direct measure of task visibility. It is assumed that if good design practice is followed, illuminance criteria can be effective. In practice, lighting designs are based on horizontal illuminance. In most cases, use of illuminance rather than luminance is more practical due to visual scene complexity. Computational procedures for horizontal illumination are much less complicated than those for luminance. This does not minimize the importance of luminance. When illuminance criteria are used as a basis for design, they must be used in such a way that adequate luminance are achieved.

An analytic model developed by the International Commission on Illumination (CIE) for describing the influence of lighting parameters upon visual performance is expected to have significant influence on development of future visibility-based illumination standards in the United States. Many of the IES-recommended target illuminances have been validated using visibility criteria. The American National Standard for Roadway Lighting, RP-8, is also currently under revision using visibility criteria.

The analytic model is a unification of Weston's (1935) classical work in which lighting was varied in quantity and resulting performance of visual tasks measured with that of Luckiesh and Moss (1937) as followed up by Blackwell (1959), where component visual processes believed to affect the relationships between lighting parameters and visual performance were studied. Fry (1962) demonstrated that regular quantitative relationships existed between empirical field test data of Weston and Blackwell's analytic data and suggested unification of these different approaches.

Illumination Design

In general, we are concerned with two basic laws involved with calculation of illumination. The inverse square law states that illumination varies directly with luminous intensity (candlepower) and inversely with distance squared. The cosine law states that illumination varies as the cosine of the angle between the light ray striking the surface and a normal to that surface. When combined, they give illumination at a point

$$E = \frac{CP}{D^2} \cos \alpha$$

where

E = illuminance in lux or footcandles

CP = candlepower of source in the direction of the point

D = distance from source to point

α = angle between source and vertical (nadir)

Geometry of the multisource illumination problem is illustrated in Figure 5.1. Illumination at any point is the sum of values contributed by each source. Designs based on this point calculation are referred to as point-by-point, or more simply, point designs. Trigonometric and vector expressions for tilt, rotation and point of aiming for each individual floodlight are essential parameters in the design process. When calculating a large number of points the value of using a computer is readily evident. Since design by the point method requires extensive calculations, use of a less complicated procedure is proposed.

A modified lumen method which is often used for preliminary evaluation of floodlight luminaires and mounting locations is ideally suited for this application. The

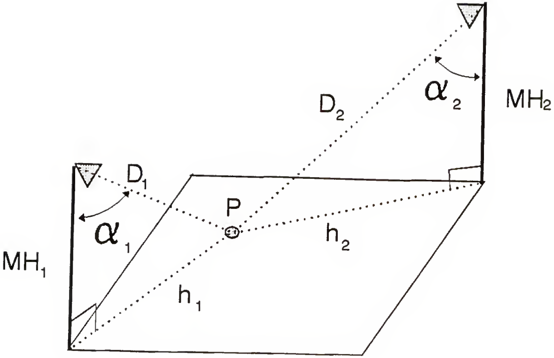


Figure 5.1 Geometry of the multisource illumination problem.

formula for calculating the average horizontal illumination on the work zone is

$$E = \frac{N x \Phi x PCU x MF}{A}$$

where

E = illuminance in lx or fc

N = number of luminaires

Φ = lamp lumens per luminaire

PCU = preliminary coefficient of utilization

MF = maintenance factor

A = area in m^2 or ft^2

Figure 5.2 presents the modified lumen equation graphically with data plotted for three principal lamp types. The preliminary coefficient of utilization is the ratio of beam lumens falling within the area to be illuminated and is assumed to be .5 for a conservative design. The maintenance factor accounts for lamp depreciation and dirt on reflecting and transmitting surfaces of the equipment. Values of .65 to .85 were used to derive the lines in the figure. The lines have also been shifted to the right to account for anticipated variability of 25%. Using this figure, recommended watts/square meter can be estimated for a given level of illuminance and lamp type.

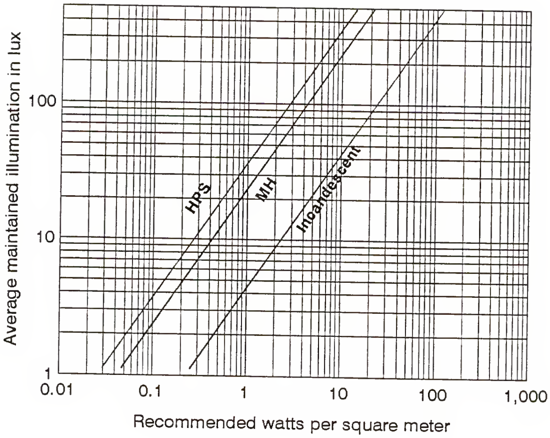


Figure 5.2 Recommended watts/square meter for different illumination levels.

Design Procedure

Illumination based designs rely on the amount of light flux reaching working surfaces and light uniformity on that surface. The steps in the design process are as follows:

1. Assess the work zone to be illuminated.
2. Select the type of light source.
3. Determine recommended lighting levels and watts/square meter.
4. Select lighting fixture locations.
5. Determine luminaire wattage.
6. Select luminaire and aiming points.
7. Check design for adequacy and glare.

These steps are arranged in the order in which they normally occur in the design process and can be applied to a completely new design or a design based on specific equipment. The process is iterative and should be repeated until the required criteria are met. It is assumed the design will be accomplished by an individual with some engineering background but limited lighting experience.

Step 1. Assess the work zone to be illuminated. Important considerations here are physical dimensions and work zone layout. By keeping the work zone rectangular in shape, total area can be computed easily. It may be necessary to define multiple work zones rather than one large area, for example, opposite ends of a paving machine. This step also provides initial opportunity to minimize glare.

Normal lines of sight for motorists and workers should be defined and monitored throughout the process.

Step 2. Select the type of light source. The type of light source selected determines important factors such as lumen output, energy requirements, lamp life, color and optical controllability. The type of source selected in this step will affect the rest of the design process. Refer to Table 3.2 for recommended applications.

Step 3. Determine recommended lighting level and watts/square meter. Recommended lighting levels will normally be specified in terms of average maintained illumination and can be found in project specifications or recommended practices discussed previously. Appendix D is a recommended standard recently developed by University of Florida researchers for the National Cooperative Highway Research Program. It will be used as criteria for designs in this study. To determine watts/square meter, enter Figure 5.2 at the recommended illumination level on the left axis and project horizontally to the appropriate lamp line and then drop down to recommended watts/square meter on the horizontal axis.

Step 4. Select fixture locations. Fixture locations in both vertical and horizontal planes can be selected based on knowledge of site imposed constraints. This would include considerations such as equipment dimensions, nearby lighting, motorist and worker lines of sight, nearby buildings, and local restrictions. In order to maintain adequate uniformity an accepted rule of thumb is that separation between luminaires should not exceed two to four times the mounting height. A more conservative approach is to limit spacing on unidirectional nominally interlaced systems to twice the mounting height. For multidirectional well interlaced systems, spacing should not exceed three mounting heights. As pole spacing increases so does uniformity ratio. This step provides the number of poles or locations to be used in later calculations.

Step 5. Determine luminaire wattage. Total lamp watts needed for an area can be calculated

$$W_t = A \times W_A$$

where

W_t = total watts needed for an area

A = area in m^2

W_A = watts/square meter from Figure 5.2

Required luminaire wattage at each mounting location can then be calculated

$$W = W_t/n$$

where

W = required luminaire wattage at each pole or mounting site

n = number of poles or mounting sites

This provides the required luminaire wattage at each mounting location.

Step 6. Select luminaires and aiming points. Knowing required wattage and beam spread, a specific luminaire can now be selected using manufacturer's data and beam spread information of Figure 4.3. Luminaires should be selected based on desired light distribution characteristics such as beam shape and cutoff. It may be necessary or helpful to use more than one luminaire at each location particularly when low mounting heights restrict source lumens as shown in Figure 4.4.

Table 5.5 can be used to determine maximum aiming line separation when luminaires are mounted adjacent to each other. Care should be taken to aim lights away from any oncoming traffic to reduce glare problems. For normal area lighting aiming points should be 2/3 to 3/4 the distance across the area or twice the mounting height whichever is lowest. Use of higher aiming angles will not improve utilization or uniformity. As a rule of thumb, highest horizontal illumination from a floodlight occurs when it is aimed at an angle of 53 degrees. This is the angle formed by a 3, 4, 5 triangle as shown in Figure 5.3. This relationship can also be used to determine mounting height as a function of preferred aiming point.

Step 7. Check design for adequacy. As a final step in the design process, check for adequacy using the five-point

Table 5.5

The Relationship between Beam Spread and Aiming Line (GE, 1992)

NEMA Type	Horizontal Beam Spread	Suggested Maximum Aiming Line Separation
2	18° - 29°	12°
3	29° - 46°	24°
4	46° - 70°	40°
5	70° - 100°	60°
6	100° - 130°	90°
7	130° +	120°

method as outlined in Appendix C or computer analysis. The importance of this step cannot be overemphasized. Use of the design process does not guarantee satisfactory results in all cases. Certain combinations of beam shape, mounting height, tilt, and lamp rating provide unpredictable responses. The contribution from every luminaire within eight mounting heights needs to be calculated for the points of interest. This will serve to verify the quantity of illumination in critical areas and if a representative cross section of the work zone is selected, average illumination and uniformity can also be evaluated. If either criterion is not satisfied, repeat the design process with the appropriate modification to location, spacing, luminaire, aiming point, or mounting height.

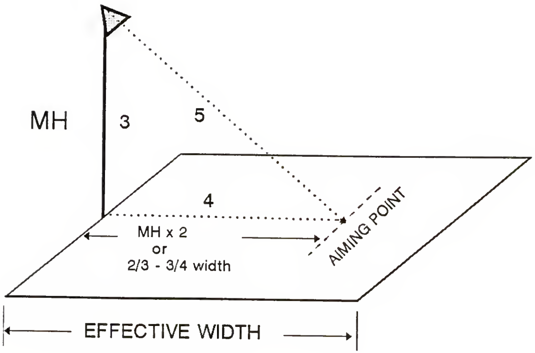


Figure 5.3 The relationship between mounting height and aiming point (GE, 1992).

Design Accuracy

Accuracy of an illumination design is a function of the detail used in the design process. Average illuminance designs based on wattage and luminaire type are considered accurate to within ±25%. Further accuracy up to ±5% can be gained by using more complex and expensive procedures. The upper limit is established by uncertainty in measurement. For purposes of assessing illuminance as it relates to vision- and visibility-related lighting systems, the ±25% accuracy is considered sufficient by the IES (IES, 1993). Recognizing that an illumination level that is 25% lower than specified levels might not be acceptable, the data of Figure 5.2 have been adjusted to provide a more conservative design by inducing variability on the high side. It should also be noted that this design procedure is a very rough approximation, and if all of the design parameters are optimized, there will be a tendency for the overall design to be suboptimal. For this reason it is also recommended that calculated luminaire wattage be rounded up to the next available standard lamp rating.

Analysis of the adequacy check using the five-point method has shown it to be a reliable and fairly precise indicator of the desired system performance. Experiments were conducted using three different beam spreads and a 100-watt metal halide luminaire. Tilt angle was rotated from 0 to 60 degrees with a fixed mounting height. At 10-degree increments average illuminance was calculated using the five-point method and compared to statistical reports generated by AGI software. The average error computed over 21 samples was -8.2%. For tilt angles between 40 and 60 degrees the error improved to -6%. By consistently erring on the low side, the technique serves its intended purpose as a conservative indicator.

Computer Design Applications

As lighting design software becomes more affordable and available, it will become a most useful tool in the design of illumination for construction work zones. In theory, the design process will follow that described previously through step 5. The major benefit of computers will be in step 6, checking design adequacy. Here, designers can actually model work zones including obstructions, define boundaries, and accurately evaluate illumination for any point or area. Computer software also provides computations of average illumination and uniformity for specified areas. If the designer is not satisfied with results, it is a simple matter to modify quantity, location, type, and aiming point for any number of luminaires. Sample computer output for a typical work zone is provided with the case studies in Chapter 8.

Glare Evaluation

The greatest challenge facing lighting designers is that associated with glare. Evaluation of glare has traditionally been very subjective using scales such as borderline between comfort and discomfort (BCD). Various computational procedures have been proposed. In general, they closely parallel point methods of calculating illuminance. In effect, they are calculating the vertical illuminance at a point as opposed to horizontal. Viewers' exposure to particularly high values of source luminance is the primary concern.

Rather than associate some empirical value with different levels of glare, the goal of glare evaluation is to recognize causes of glare and treat them in the design process to the maximum extent possible. There are several basic techniques that have been incorporated within the design process that will help reduce glare. These include the selection of aiming point away from common lines of sight, the coordination of luminaire wattage with mounting heights, and the minimization of the vertical angle of incidence with respect to nadir, as presented in the glare avoidance checklist of Table 4.2.

At the conclusion of the design process, the illumination system should be viewed in its entirety. If recommended procedures have been followed and there still appear to be potential problems with glare, use of glare-avoidance devices such as lamp inserts, hoods, and barriers is recommended.

Summary

The basic design procedure outlined in this chapter is simple enough to be accomplished by an individual with some engineering background but limited lighting experience. The procedure can be used with or without computers. It requires a basic knowledge of lamp characteristics and access to manufacturers' photometric data. Although a completely new design is assumed, it can also be used as a very quick method to evaluate existing systems. Checking the adequacy of the design is a necessary step and will ensure positive results. Should a higher degree of precision be required in the design process, the use of computer design software would be recommended.

CHAPTER 6
SYSTEM OPERATION AND MAINTENANCE

Introduction

Lighting system effectiveness clearly depends on a good design in initial development. An equally important and often overlooked aspect of continued effectiveness is proper operation and maintenance of the lighting system. To assure intended lighting quantity and quality, whether for task performance or safety reasons, lighting systems must be properly operated and maintained. Another important consideration is expected system reliability. Project delays due to malfunctioning illumination systems could be very costly, especially when materials with specified placement times, such as concrete and asphalt, are involved. Important concerns of power source maintenance, hardware maintenance, and provision of backups address stated objective five of this research and are the basis of discussion for this chapter.

Power Source Maintenance

Operation of any lighting system is dependent on provision of power. In a construction work zone power is available from three different sources: line, portable generators, and alternators installed on the construction equipment. Periodic monitoring of the power supply will assure proper lighting system operation.

Power systems are typically characterized by voltage and could range from a low of 12 volts to as high as 480 volts or more. As a general rule, lamps should be operated at rated voltage. Overvoltage operation results in a drastically reduced lamp life. However, wattage, efficacy, and light output are improved. Operating undervoltage will increase lamp life with corresponding reductions in wattage, efficacy, and light output. Characteristic curves for an incandescent lamp provided as Figure 6.1 indicate a voltage as little as 5% below normal results in a loss of light amounting to more than 16%. Similar relationships hold for other types of lamps. Maintenance of proper voltage is, therefore, an important factor in obtaining good lighting system performance.

When dealing with electricity, it is very important to be aware of the provisions of the National Electric Code. Article 305 pertains to temporary electrical power and lighting wiring methods which may be of a class less than would be required for a permanent installation, such as the construction work zone. Important provisions of this article include requirements for temporary wiring to be located where

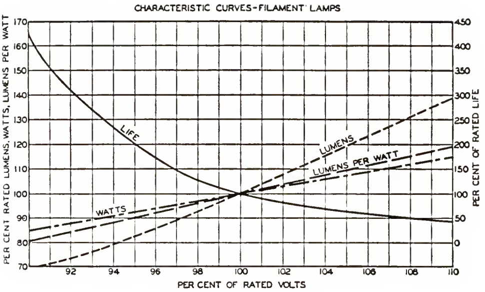


Figure 6.1 Characteristic lamp curves (Westinghouse, 1978).

it will not be subject to physical damage and for all general illumination lamps to be protected from accidental contact or breakage by a suitable fixture or lampholder with a guard as shown in Figure 6.2. There is also a provision requiring separate ungrounded conductors for lighting and receptacle loads so that the activation of a fuse or circuit breaker or a ground fault circuit interrupter due to a fault or overload of equipment will not deenergize the lighting circuit (Early, et al., 1990).

Grounding of temporary lighting systems is governed by Article 250 of the NEC which also includes provisions for grounding of portable and vehicle mounted generators. Portable generator frames are not required to be grounded and can serve as the grounding electrode for a system supplied by the generator if certain conditions are met. First, the generator may only supply equipment mounted on the generator and/or cord and plug connected equipment mounted through receptacles mounted on the generator. Noncurrent-carrying metal parts of equipment and the equipment grounding conductor terminals are to be bonded to the generator frame. The frame of a vehicle is permitted to serve as the grounding electrode for a system supplied by a generator mounted on the vehicle if the frame of the generator is bonded to the vehicle frame and the generator supplies only equipment located on the vehicle and/or cord and plug connected equipment through receptacles mounted on the vehicle or on

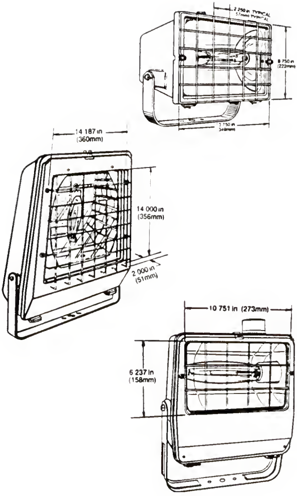


Figure 6.2 Wire guards for lamp protection per the NEC (GE, 1992).

the generator, and the noncurrent-carrying metal parts of the equipment and the equipment grounding conductor terminals of the receptacles are bonded to the generator frame (Early et al, 1990).

Lighting Hardware Maintenance

Lighting hardware maintenance is necessary to recover light losses due to effects of time and usage, such as lamp lumen depreciation, dirt accumulation on lamps and luminaires, lamp burnouts, and effects of misdirected lights. Combined effects of equipment age and dirt depreciation can reduce illuminance by as much as 50%. Much of this potential light loss is taken into account in design of systems through inclusion of maintenance factors. This provides a higher luminance at the onset than that actually recommended in design criteria.

Planned lighting maintenance has been shown to be the most effective method of consistently maintaining illuminance and lighting quantity at the lowest operating and maintenance cost. It entails group relamping, cleaning of lamps and luminaires, and replacement of broken or otherwise defective components on a scheduled basis. The system should also be monitored between scheduled maintenance activities to ensure proper and safe operation.

Group relamping has been shown to reduce the cost of operating a lighting system and also improve performance. It entails replacing all or some portion of the lamps in a system together at a fixed interval which is usually determined to be between 70% and 80% of rated life. This method is directed at systems with large numbers of lamps, and savings result from labor costs and delay costs associated with a lamp outage. It typically costs less per lamp to replace a large number at once than to replace one at a time as they fail. Lighting quality is maintained in addition to presenting the opportunity for other maintenance and cleaning.

A construction environment poses a higher than normal exposure to effects of dirt accumulation and resulting decrease in light output. Periodically cleaning lamps and luminaires will maintain light output and distribution at intended values. Because of high concentrations of dust or dirt in the air, it should be accomplished at more frequent intervals than group relamping.

Planned maintenance of lighting systems is more than changing lamps and cleaning. It affords the opportunity to efficiently locate and repair defective or broken components that might cause system problems. Demand or emergency maintenance is directed at known problems. This could include situations such as lamp flickering, short lamp life, no or slow starting, low output, unusual color, and blown fuses. These problems warrant immediate attention. In many cases the manufacturers troubleshooting guide for a particular system will provide a simple solution. More complicated problems should be addressed by a qualified electrician.

Throughout the design process significant attention was given to the importance of luminaire angles both vertical (tilt) and horizontal (orientation). This importance carries on into the operational phase. In order to maximize system effectiveness, luminaire positions should be monitored and maintained as specified. From a practical viewpoint, aiming luminaires precisely is not a very realistic expectation. An understanding of system sensitivities to variations in parameters is necessary.

Changes in average luminance and uniformity due to variations in mounting height, tilt, and orientation have been plotted in Figure 6.3 to 6.5. Luminaires analyzed include a very wide beam 7x7, the commonly used 6x6, and a narrow beam 3x4 that appears to have application for equipment-mounted lighting. The area to be illuminated was a 5 meter by 5 meter square with specified illuminance of 108 lux. A 100-watt metal halide lamp was selected as the source. Note that illuminance criteria is only achieved with the 3x4.

Figure 6.3 demonstrates the effects of a 1 meter change in mounting height, constant tilt and orientation. Although uniformity remains within specifications, note changes in illuminance of up to 30%. In Figure 6.4 mounting height and

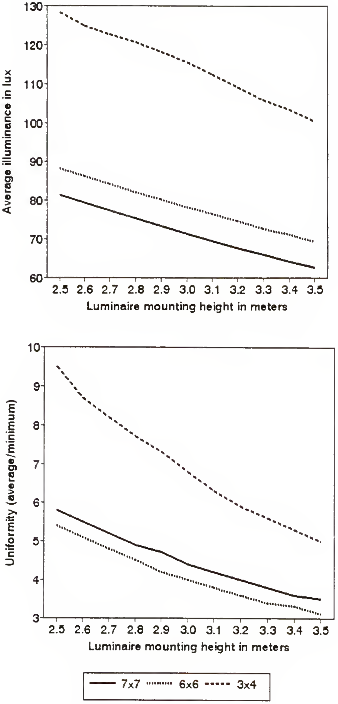


Figure 6.3 Illuminance and uniformity variations due to mounting height.

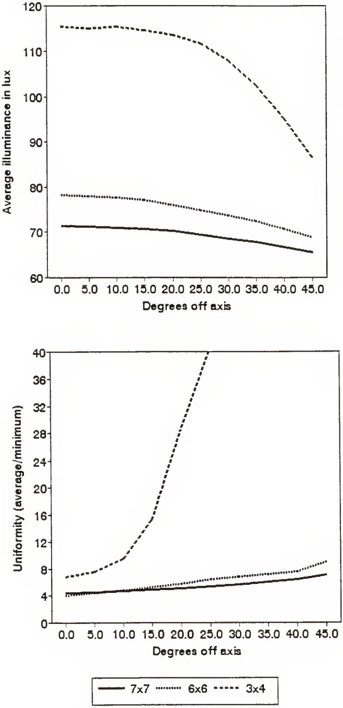


Figure 6.4 Illuminance and uniformity variations due to orientation.

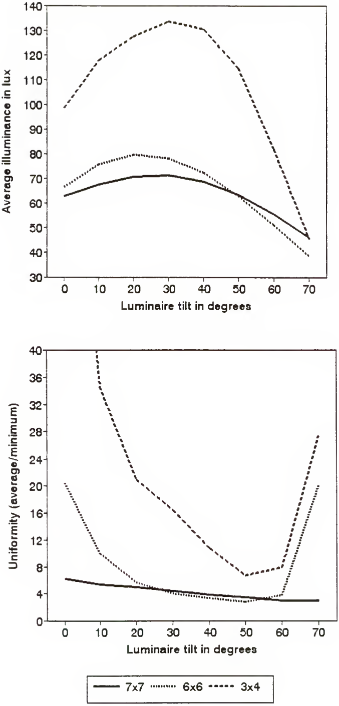


Figure 6.5 Illuminance and uniformity variations due to tilt.

tilt are constant while orientation is shifted off axis. For wide beams, effects are almost negligible. Average illuminance for the narrow beam is fairly constant through 20 degrees of shift. This is very misleading and indicates the need to use both criteria. Checking uniformity shows a rapid increase with only a 10 degree shift. Extremely high values of illuminance at the beam axis are causing this deceptive situation.

The third parameter that might vary is the luminaire tilt. Figure 6.4 shows peaking curves for all three luminaires. Again narrow beams are more responsive to variation. Comparing uniformity and illuminance curves an optimal range for wide beams could be described as 10 to 40 degrees of tilt. For narrow beams optimum average illuminance does not coincide with optimum uniformity. Since the average is being distorted by high values, uniformity should prevail and an operating area of from 45 to 55 degrees selected. This is consistent with previous discussion regarding maximum illuminance at about 53 degrees of tilt.

Backup Systems

Lighting system failure could be catastrophic and costly. From the viewpoint of safety, risk of accidents increases. From that of productivity, workers are idle and materials that need to be placed within a fixed period, such as concrete and asphalt, are wasted. Many contract specifications currently have provisions requiring standby equipment. If not, the prudent contractor should assess potential risk and costs of a blackout and then provide backup equipment accordingly. For the purpose of discussion, backup equipment will be considered as distinct from spare maintenance parts, such as lamps and fuses, that should always be available.

There are many causes of a system or component failure. Most relate to maintenance and operation. If scheduled maintenance is performed as described earlier, many potential problems can be resolved before they impact work. A common source of problems is in system operation. Users of portable electric equipment find lighting system generators a very convenient source of power. The danger here is in overloading the circuit. If the breaker trips and discharge lighting is being used, there is a potential blackout of up to 10 minutes for the reignition of the lamps. The solution is to have dedicated circuits for power tools and not allowing the lighting circuit serve as a backup source as prescribed by the NEC. It also presents a strong case for the inclusion of incandescent lamps in the lighting system to accommodate long reignition times of HID sources.

The amount of backup equipment provided will depend on the specific job and the equipment employed. For example, a work zone powered from a single generator is much more susceptible than one that uses multiple generators. Another case would be the retrofitting of a paving machine with auxiliary lights and portable generator. If this generator were to fail, operations would come to a standstill while another generator was mounted. It would certainly be worthwhile to have a second generator that will fit on the platform readily available.

Summary

Proper operation and maintenance of lighting systems is as important as design. Installation should be in accordance with the appropriate NEC provisions. Performance of routine maintenance, such as relamping, cleaning, necessary repairs, and monitoring of luminaire positioning, will assure that the system operates as intended. Although this type of program will minimize breakdowns in the field, it will not totally eliminate them, and it is highly recommended that backup equipment be provided for critical functions.

CHAPTER 7
ECONOMIC CONSIDERATIONS

Introduction

When designing lighting systems, a primary concern should be provision of sufficient amounts of quality light at a reasonable cost. Economic impacts of lighting requirements could very well be significant and certainly warrant consideration during bid preparation. Through application of accurate cost analysis, it is possible to evaluate alternative approaches, determine impact of the lighting system on construction schedules, manage budget and cash flow, quantify benefits of various systems, and, in general, simplify the complexities of lighting systems into cost, a basic language that is easily understood.

Many techniques are available for analyzing economics of a lighting system. A useful approach to analysis of somewhat dissimilar lighting systems is to evaluate quantity and quality factors in terms of dollars and cents. It is then possible to compare cost or benefit of specific installations on the basis of equal levels of illumination of the same quality. This chapter highlights important factors and provides a general framework from which any economic analysis can proceed.

Cost Elements

Total cost of light can be computed by assembling all elements of both fixed and variable charges which are relevant to a particular configuration. This total can then serve as a comparison of the cost of light with other units of production or as a comparison of various lighting systems.

Fixed costs of any lighting system are most often associated with initial installation. This would include cost of installation labor and hardware such as lamps, luminaires, ballasts, wiring, and mounting devices to include poles and brackets. If any shielding systems are used, they would also be included as fixed costs. Costs of generators and portable light towers are also considered fixed although they might be incurred over time rather than initially.

Variable costs are those that are related to the operation and maintenance of the system. This normally includes energy costs, replacement lamps, and maintenance labor. These costs will vary with system utilization and longevity for specific lamp types. A summary of cost elements is provided in Table 7.1.

When determining total cost, care should be taken to include anticipated reuse of materials. For example, if the work zone is 9 kilometers long and the design calls for a light source every 30 meters, it might not be necessary to illuminate all 9 kilometers simultaneously. If the construction plan calls for work to be done in 1 kilometer sections, it would only be necessary to procure 33 light sources with each being reused 9 times. Coordination of lighting plan with construction schedule development is a crucial step in the planning process.

Table 7.1

Cost Element Summary

Basic Data	Number of Lamps
	Lamp Life (hours)
	Energy Rate ($/KWH)
	Generator Fuel (Gal/Hr x $/Gal)
Initial Cost	Luminaires
	Lamps
	Wiring
	Mounting Hardware
	Labor
	Equipment Rental (towers)
	Generators
Operating Cost	Power (electricity or fuel)
	Replacement Lamps
	Maintenance Parts
	Maintenance Labor

Analysis on a total cost basis appears to be the most practical approach to this problem. Since the duration of most projects is less than one year, it can be reasonably argued that there is no need to be concerned with time value of money and application of discount factors. This lump sum approach provides meaningful information to the contractor for bidding purposes. Awareness of operation and maintenance costs will also be helpful in the management of budget and cash flow throughout the project duration.

For purpose of comparisons, approximate costs have been developed for each configuration discussed in Chapter 4. It is estimated that temporary system costs could run as much as $67,000 per kilometer to install and operate, while portable systems would be approximately $37,000 per kilometer. Cost of equipment-mounted systems does not lend itself to a per mile analysis. For comparison, it has been estimated at less than $2,000 per piece of equipment. A normal suite of equipment for a project could include 15 to 20 pieces, resulting in a total cost of about $40,000. After converting costs of temporary and portable systems to a total cost basis for comparison, use of equipment-mounted systems appears highly desirable assuming illuminance and uniformity criteria are equivalent.

Benefits

Benefit-cost ratio analysis is a technique that has found considerable application in government projects. Simply stated, if benefits exceed cost, there is definite value to the alternative under consideration. The difficulty in using this approach is in quantification of benefits. While benefits are widely understood to mean cost savings, in many cases there is no direct income, and other benefits both tangible and intangible must be considered very carefully.

From the public's viewpoint, benefits would include traffic safety and minimal delays. From that of the contractor, benefits would include improvements in safety, quality, and productivity. Although previous research has suggested such a correlation exists, it remains to be quantified. When these data become available for nighttime construction activities, it is anticipated that benefit-cost ratio analysis will find widespread acceptance and usage since it provides an easily understood figure of merit.

Summary

The purpose of this chapter has been to delineate those elements contributing to the cost of illuminating a construction work zone. Calculation of total cost provides important information to management that can be used for bidding, scheduling, and project financial control. Although not quantified at this time, there are also clear economic benefits associated with quantity and quality of illumination provided. An overall awareness of economic costs and benefits is essential to further development of nighttime construction operations.

CHAPTER 8
CASE STUDIES: PRACTICAL APPLICATIONS

Introduction

To demonstrate the use of the previously developed design procedure and show its flexibility, designs for three basic configurations will be discussed. Each configuration poses a different problem to the lighting designer. Temporary lighting has relatively few design constraints while use of portable lighting equipment constrains designs to specific heights and luminaires. After some analysis of equipment characteristics and lighting criteria, it becomes evident that a few standardized lighting plans will satisfy most situations. Computer simulations will be provided for each design to demonstrate results and validate the adequacy of procedures.

A very common type of project performed at night and requiring illumination is resurfacing of a two-lane highway. Average length for this work zone is usually about 9.6 kilometers. Typical lane widths are 3.7 meters, as shown in Figure 8.1, and median width varies. Work to be accomplished is classic linear construction in two northbound lanes which includes milling and removal of existing asphalt and

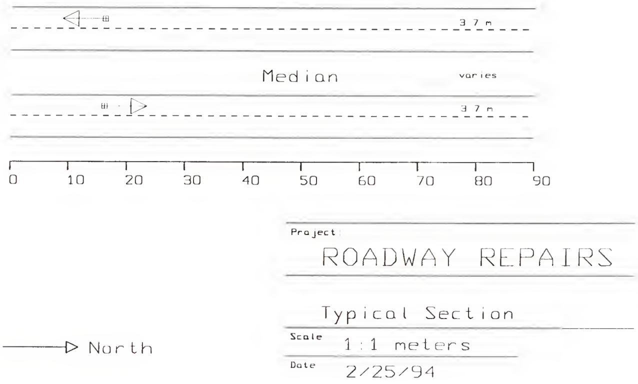


Figure 8.1 Example project.

resurfacing. Contract specifications require one lane be open at all times and illumination provided in accordance with criteria of Appendix D.

Case One: Temporary Lighting

Step 1. Assess the work zone to be illuminated. Traffic will be flowing both directions near the work zone. Most construction activity will flow with traffic. In order to eliminate the need for reconfiguring the system for work on each lane, lighting will be provided for both lanes concurrently. This will also eliminate problems associated with light spillage from the work zone onto adjacent traffic lanes. The area to be illuminated is 7.4 meters wide and 9.6 kilometers long or

$$A = 71{,}040 \text{ square meters}$$

No height constraints are given. Lights will be mounted on temporary wooden poles placed along the outside edge of the roadway with a setback of 2.6 meters. Three principal lines of sight should be monitored during design. Equipment operators and traffic for the lanes under repair will normally be operating in the same direction. Visual comfort of traffic in the two opposite flowing lanes is also of concern.

Step 2. Select the type of light source. Since the area to be illuminated is quite large, color is not an important factor, and there are no height constraints, high pressure sodium lamps are chosen. From Table 3.1, they are rated high in output, efficacy, life, and maintenance of output.

Step 3. Determine recommended lighting level and watts/square meter. From specified criteria and description of work to be performed, recommended lighting level is found to be 108 lux (10 footcandles) with a uniformity ratio of 10:1. Enter Figure 5.2 at 108 lux and move across to high pressure sodium. Drop down to the horizontal axis at this point to find

$$W_A = 3.0 \text{ watts per square meter}$$

Step 4. Select fixture locations. Assume fixtures are to be mounted on available 12-meter wooden poles along the east shoulder of the roadway. Using pole spacing criteria of 2 to 4 times mounting height, select 36 meters. Total number of poles can be determined by dividing overall distance of 9,600 meters by 36 meters/pole. From this calculation

$$n = 267 \text{ poles}$$

Step 5. Determine luminaire wattage. Multiply area of 71,040 square meters by 3.0 watts per square meter and divide by 267 poles to determine that

$$W = 798 \text{ luminaire watts per pole}$$

Step 6. Select and orient luminaires. Select two 400-watt high pressure sodium (HPS400) luminaires to achieve required 798 watts at each pole. Since poles are along one edge and the work zone is relatively narrow, a wide beam, short throw pattern is suggested. From Figure 4.3, type 6 has a wide beam and projection of about 32 meters. To minimize vertical brightness, consider a cutoff or type 2, 3, or 4 vertical beam. From available manufacturers' data a 6Hx3V model is chosen. Photometric report number 177748 in Appendix E corresponds to the selected luminaire. Referring to Table 5.5, type 6 floodlights should be aimed such that their aiming lines are separated by no more than 90 degrees. Luminaire tilt should be set between 60 degrees (aiming point at twice the mounting height) or 38 degrees (aiming point at two-thirds diagonal width based on a perpendicular width of 10 meters and a horizontal angle of 45 degrees). Select 38 degrees tilt. The system is now completely specified.

Step 7. Check design for adequacy and glare. Design adequacy can be checked with either computer modeling or five-point calculations by designating a representative statistical area and drawing the diagonal as shown in Figure 8.2. The isolux lines shown in this and ensuing figures represent the target illuminance of 108 lux and the OSHA minimum illuminance of 54 lux. Computed average illuminance of 60.8 lux does not meet desired criteria, and adjustments are necessary. Options include increasing wattage and

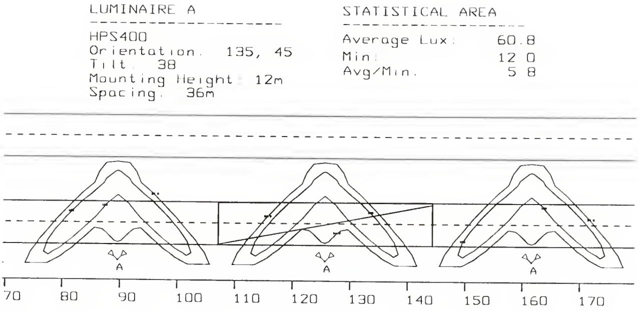
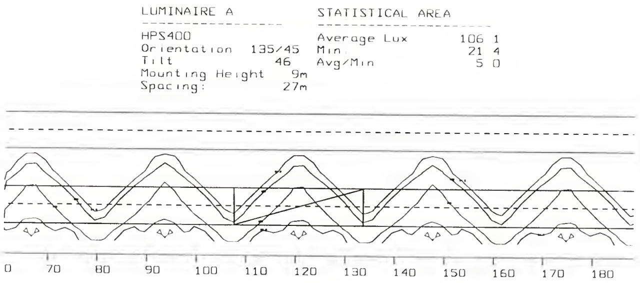


Figure 8.2 Results of computer modeling for temporary lighting system.

mounting height or reducing mounting height and spacing. From manufacturers literature, the next available lamp is rated at 1,000 watts and 140,000 lumens. Note from Figure 4.4 that this corresponds to a minimum mounting height of 16 meters which extends the height of available poles. Also note that for HPS400 the minimum mounting height is 9 meters. Repeating the calculations for a 9 meter mounting height and 27 meter spacing (3 times mounting height) results in 356 poles, 599 watts/pole and a choice of lamp tilt angles between 46 and 60 degrees. Selecting 46 degrees results in light distribution as shown in Figure 8.3. Average illumination is 106 lux, and the ratio of average to minimum is 5.0.

After determining adequacy of light levels and their uniformity, use the glare checklist of Table 4.2 to ensure that every effort has been taken to minimize glare. In this particular application, it is difficult to avoid aiming the lights toward the principal lines of sight due to the physical constraints on the locations of the poles. However, the 45-degree criterion has been achieved for both directions of traffic flow. It is very important that source brightness and mounting height criteria be adhered to in addition to minimization of luminance at 72 degrees above the nadir. Mounting height was addressed in the design. With the main beam at 46 degrees, it is necessary to ensure that the table values above 26 degrees (72-46) on the photometric report do



```
LUMINAIRE A                 STATISTICAL AREA
-----------------           ---------------------
HPS400                      Average Lux       106 1
Orientation   135/45        Min                21 4
Tilt              46        Avg/Min             5 0
Mounting Height    9m
Spacing:          27m
```

Figure 8.3 Results of computer modeling for adjusted temporary lighting system.

not exceed 20,000 candela. The selected luminaire cuts off at 25.5 degrees; hence, brightness above 72 degrees is not an issue. If there were a problem, the use of glare screens, louvers, or visors should be considered.

Case Two: Portable Light Towers

Step 1. Assess the work zone to be illuminated. This is the same situation described previously except the contractor is considering the use of portable light towers that are available through an equipment rental company. Trailers will be placed on the inside or west edge of the road along the median and the towers will be raised to their maximum height of 9 meters.

Step 2. Select the type of light source. Each rental unit is equipped with four 1000-watt metal halide (MH1000), general purpose, 5Hx5V floodlights. Referring again to Table 3.1, they are rated high in output and good in all other areas.

Step 3. Determine recommended lighting level and watts/square meter. Recommended lighting level remains 108 lux. Enter Figure 5.2 at 108 lux and move across to the metal halide line. Drop down to horizontal axis at this point to find

$$W_A = 4.5 \text{ watts per square meter}$$

Note metal halide is not as efficient as high pressure sodium.

Step 4. Select fixture locations. Fixtures are mounted on 9-meter towers along the edge of the roadway. As before, maximum allowable space between towers will be 36 meters; however, luminaires will not be as strongly interlaced since they will all be aimed in the same direction. A spacing of 20 meters or slightly more than twice the mounting height will require

$$n = 480 \text{ trailers}$$

or 50 trailers per kilometer.

Step 5. Determine luminaire wattage. Multiply area of 71,040 square meters by 4.5 lamp watts per square meter and divide by 480 to determine

$$W = 666 \text{ watts per tower}$$

Each tower is actually equipped with 4000 watts so it will only be necessary to use one of the floodlights on each tower. Had a spacing of 30 meters been selected, 999 watts per tower would have been necessary and two floodlights recommended.

Step 6. Select and orient luminaires. As before, the work zone is relatively narrow and a wide beam, short throw pattern is suggested. The 5x5 floodlight might present some glare problems due to vertical beam height.

In order to take advantage of the floodlight range, it should be aimed in the direction of traffic flow in the nearest lane to form a horizontal angle of approximately 45 degrees from the perpendicular relative to the roadway. The luminaire tilt should be between 40 and 60 degrees, where 40 degrees corresponds to a distance of two-thirds the width. Try 40 degrees.

Step 7. Check design for adequacy and glare. Recall this design was constrained by available equipment. The computer printout of Figure 8.4 shows that desired criteria have again been satisfied with an average maintained illuminance of 238.7 lux and an average-to-minimum ratio of 4.8.

Application of the glare checklist indicates several potential problems. Minimum mounting height for a MH1000 is 14 meters. The equipment is limited to a maximum of 9 meters. For a luminaire tilt of 40 degrees, the values above 32 degrees (72-40) on the photometric report should be less than 20,000 candela. Referring to report 177461 in Appendix E, at 32 degrees the value is 35,300 candela. This can be rectified by reducing the angle or adding a hood or louvers, the effects of which are shown in Figure 8.5. Recomputed average maintained illuminance and uniformity are both excellent. A check of photometric report 178400 indicates no objectionable values.

```
STATISTICAL AREA  WORK ZONE
---------------------------
AVERAGE lux= 240 73
MAXIMUM = 549
MINIMUM = 49 7
AVERAGE/MINIMUM = 4 84
MAXIMUM/MINIMUM = 11 05
```

NO	LUMINAIRE LABEL	X-COORD	Y-COORD	Z-COORD	ORIENT	TILT	AIMING COORDINATES X	Y	Z
1	MH1000	10	44	9	315	40	15	39	0
2	MH1000	30	44	9	315	40	35	39	0
3	MH1000	50	44	9	315	40	55	39	0
4	MH1000	70	44	9	315	40	75	39	0
5	MH1000	90	44	9	315	40	95	39	0
6	MH1000	110	44	9	315	40	115	39	0
7	MH1000	130	44	9	315	40	135	39	0
8	MH1000	150	44	9	315	40	155	39	0
9	MH1000	170	44	9	315	40	175	39	0
10	MH1000	190	44	9	315	40	195	39	0
11	MH1000	210	44	9	315	40	215	39	0

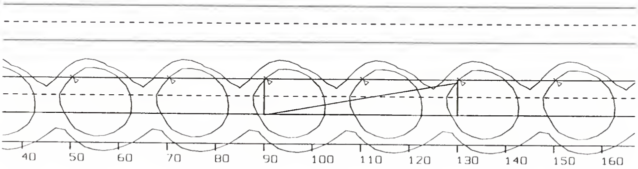


Figure 8.4 Results of computer modeling for portable lighting system.

```
STATISTICAL AREA .WORK ZONE
----------------------------
AVERAGE lux= 245 91
MAXIMUM = 627
MINIMUM = 54.8
AVERAGE/MINIMUM = 4 49
MAXIMUM/MINIMUM = 11 44
```

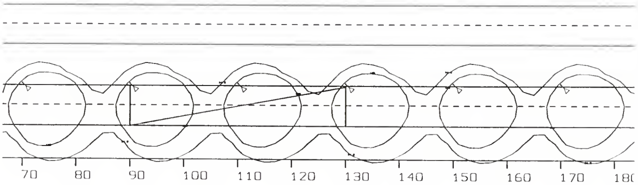


Figure 8.5 The effect of full glare control devices for the portable lighting system.

Case Three: Equipment-Mounted Lighting Systems

Step 1, Assess the work zone to be illuminated. Although this case is based on the exact same work zone as the previous two, it must be approached in a very different manner. Here the contractor will rely only on equipment-mounted lighting. It becomes necessary then to analyze the equipment to be used and the work zones associated with each specific piece of equipment. Table 8.1 summarizes the equipment and respective work zones based on operator visual tasks and the criteria of Appendix D. The critical lines of sight remain as discussed previously.

Step 2. Select the type of light source. Due to the low mounting heights and moderate areas of coverage, low wattage metal halide lights will be most appropriate for this particular application. From Figure 3.1, they are rated good in control which is an important consideration when dealing with task lighting.

Step 3. Determine recommended lighting level and watts/square meter. Recommended lighting levels and watts per square meter are summarized in Table 8.2. The values were obtained as before using Figure 5.2 and the metal halide source line.

Step 4 Select fixture locations

Fixture locations will be constrained by the physical characteristics of the construction equipment. Figures 8.6

to 8.9 show the general positioning of the lights with respect to the equipment.

Table 8.1

Equipment Work Zone Requirements

Type	Dimensions	A	Note
Milling machine	4.9 x 3.3	16.2	Front & rear
Front loader	17.7 x 3.3	58.4	Front
Sweeper	17.7 x 3.3	58.4	Front
Paver	4.9 x 3.3	16.2	Front & rear
Roller	17.7 x 3.3	58.4	Front & rear

Table 8.2

Recommended Lighting Levels and Watts/m^2

Type	Level lux	W	Required Watts
Milling machine	108	4.0	65
Front loader	54	2.5	146
Sweeper	54	2.5	146
Paver	108	4.0	65
Roller	108	2.5	233

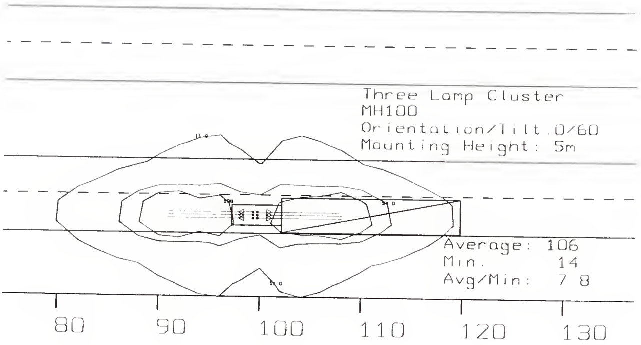


Figure 8.6 Roller lighting plan and distribution.

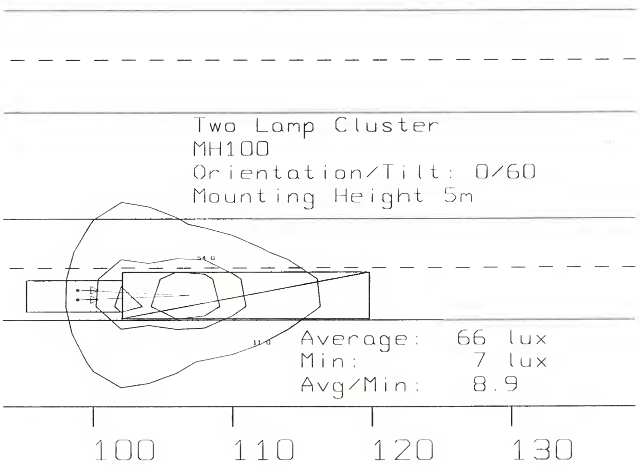


Figure 8.7 Sweeper/front end loader lighting plan and distribution.

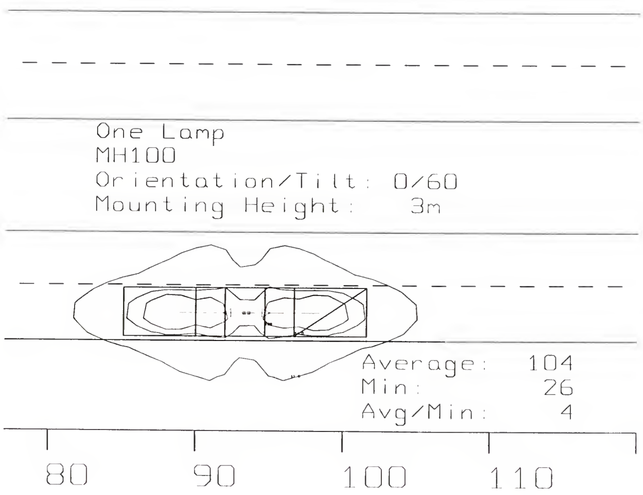


Figure 8.8 Paving machine lighting plan and distribution.

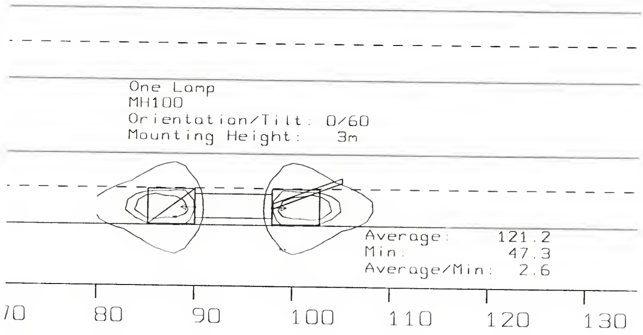


Figure 8.9 Milling machine lighting plan and distribution.

Step 5. Determine luminaire wattage. Required wattage is summarized in Table 8.2.

Step 6. Select and orient luminaires. In order to use the same luminaires on all of the equipment, a 100-watt (MH100), 3Hx4V luminaire as described on photometric report 178572 is selected. Narrow beam width is desirable to minimize light spill to the sides yet also project an adequate distance to cover the longer 17.7 meter work zone. Luminaires will be clustered to achieve illuminance criteria. Tilt angles from 50 to 60 degrees were utilized as shown in Figures 8.6 to 8.9.

Step 7. Check design for adequacy and glare. Computer simulations and point calculations were performed for each piece of equipment followed by the glare checklist. All criteria have been satisfied.

Summary

Case One illustrates that the design procedure does not always provide the expected results. It is an iterative process requiring checks and adjustments for best results. Point procedures based on 5 points provided reasonably accurate calculations of the average illuminance and uniformity ratio in each case.

Effective use of the glare checklist and control devices was shown in case two. The final example demonstrated the illumination of a small suite of equipment while emphasizing the use of compatible lights to reduce maintenance problems and expense. Similarity of work zones became evident early in the design process, thus reducing the number of actual designs required for five pieces of equipment to three.

CHAPTER 9
SUMMARY AND CONCLUSIONS

Introduction

As our nation's infrastructure deteriorates with age, there will be continuously emerging requirements to make alterations and repairs to essential systems with minimal disruptions to operations or public use. Performance of work during nighttime hours has materialized as an extremely effective approach to this problem. With as much as 20% of the highway work being performed at night, development of illumination guidelines would be beneficial to contractors as well as government agencies. An added benefit would be increased safety for the public.

Temporary lighting or construction work zone lighting has received very little attention from construction, illumination and safety communities. Although universally recognized and accepted that performance and job site safety are directly related to quality and quantity of light, the construction industry has failed to adopt a standard for work zone lighting. A review of contract clauses pertaining to lighting from various state specifications has shown no consistency and in some cases requirements that are either highly impractical or pose an outright hazardous situation.

To rectify the problem as stated above, this research has resulted in development of guidelines for illumination of nighttime linear construction activities such as highway work. It provides a tool that can be used by contractor and inspecting agency to design and configure or validate proposed illumination systems while satisfying existing or any foreseeable design criteria. It also addresses comfort and safety of passing motorists through a systematic procedure for reduction of glare.

Research Objectives

This research focused on developing a systematic approach that can be used by engineers, construction personnel, and inspectors in order to design and implement illumination systems for nighttime highway construction and maintenance operations. In order to present the guideline in a form that can be easily understood, it was necessary to gain a thorough understanding of lighting concepts, nighttime construction operations, and capabilities of available light sources. A primary requirement of the guideline is development of a robust manual design process that is simple to use. Implementation aspects were to be addressed by discussions on operations and maintenance in addition to economic considerations. Accuracy of the design procedure was to be validated through comparison of results using the statistical capabilities of a lighting design software. As a final phase, practicality and utility of the procedure was to be demonstrated using actual highway projects.

Summary

Objectives of this research were accomplished in four phases by analyzing and organizing major factors that have been found to contribute to well-designed illumination systems in addition to environmental factors associated with nighttime construction work zones.

The first phase in development of the systematic procedure began with a literature review of previous relevant work as well as field observation of current practice. This was essential to an understanding of the construction environment and factors to be considered. This was followed by the second phase in which currently available lighting hardware was analyzed in addition to existing design procedures to determine their applicability to this particular problem. It also addressed important issues of glare and how to reduce its impact on passing motorists.

Phase three was concerned with implementation or effective use of lighting systems and specifically addressed operation and maintenance. The fourth and final phase dealt with economic aspects of lighting systems as well as the practical applications. Three different configurations for the same work zone demonstrated the design procedures effectiveness and accuracy was validated through computer modeling.

Conclusions

This research produced a tool intended for use by the construction industry. Contract administrators will also find it helpful for making a quick review of contractor submittals. In order to maintain practicality and utility, the design procedure is necessarily simplistic.

Based on observations of current procedures on many jobsites, the quality of work zone illumination can be dramatically improved by following these guidelines in particular the glare check list. With nothing more than basic guidance and an understanding of hazards associated with misdirected lighting systems contractors and government agencies can enhance safety of nighttime highway work zones. The developed guidelines take a systems approach to the illumination problem through analysis of the entire life cycle including requirements, design, and operation.

Quality illumination systems require continued attention, particularly when located in a construction work zone. The most important factor in maintaining the quality of illumination is luminaire aiming. It not only affects quantity and quality of light in the work zone but is also a very significant factor in reducing hazards of glare to passing motorists.

Procedures contained in this guideline are advisory in nature and not proposed to be implemented as a standard. They merely provide an approach to the illumination problem based on existing hardware and illuminance criteria. The use of innovative systems and techniques to illuminate construction sites is strongly encouraged.

Recommendations for Future Research

During the course of research for this study, several areas that need further study were identified. These areas include

1. Development of consistent and attainable state standards. The preparation of standard specifications would encourage implementation of quality lighting systems in addition to development of packaged systems that would reduce the cost of illumination.

2. Development of engineered lighting systems for construction equipment. Construction equipment manufacturers or manufacturers of after market lighting products would benefit from a knowledge of photometric characteristics of their equipment. Again, this would encourage further development and high quality illumination.

3. Expert systems to assist in the design process. The process described in this guideline is a prime candidate for

expert systems implementation. Proper application of artificial intelligence technology to the selection of equipment and design of illumination systems would enhance implementation.

4. Development of management data for nighttime construction. With implementation of standardized lighting systems, the nighttime construction environment is more conducive to statistical analysis. A great deal of data collection and analysis in areas of cost, safety, productivity, and quality can now be performed.

5. Development of empirical approaches to evaluate glare. With technological advances in available instrumentation, the measurement of glare or glare associated parameters is a reality. Computation of these parameters is possible with lighting design software. It only remains to define specific glare criteria.

APPENDIX A
LIGHTING EQUIPMENT MANUFACTURERS CONTACTED

AAMSCO Lighting

ABS Lighting Corp.

AC-DC Equipment Co.

ADRA Electric Products, Inc.

Almand Bros., Inc.

Alpha Lighting Industries,
Inc.

American Electric Lighting
Division of Thomas & Betts

American Lighting
Corporation

American Scientific Lighting
Corp.

Ameriel Airport Lighting
Inc.

Amida Industries, Inc.

Arrow Safety Device Company

Brownlee Lighting

Coleman Engineering

Collins Enterprises

Condor Mfg. Corp.

Crouse-Hinds

Crouse-Hinds Lighting

Day-Brite Lighting
Division of Thomas
Industries

Diversified Lighting
Products, Inc.
Engineered Lighting Products

Flex-Lite, Inc.

GE Lighting

GE Lighting Systems

Holophane Company, Inc.

Indus-tool

Keene-Widelite

Lithonia Lighting

LSI Lighting Systems
Division of LSI Industries

Lumenyte International
Corporation

McGraw-Edison
Brand of Cooper Lighting

Magnaray International
Division of World
Institute of Lighting &
Development Corp.

MagniFlood, Inc.

Musco Lighting, Inc.

OSRAM Corporation

Peerless Lighting
Corporation

Philips Lighting Company

Prescolite
Division of USI Lighting,
Inc.

Qualite Sports Lighting,
Inc.

Ruud Lighting

Specialty Lighting
Anaheim, CA

Specialty Lighting
Shelby, NC

Sure-Lites
Brand of Cooper Lighting

Sylvania Lighting

Task Lighting Corporation

Technical Lighting Systems

Thomas Industries, Inc.

Toshiba America Consumer
Products, Inc.

Vista Manufacturing, Inc.

W. F. Harris Lighting, Inc.

Wagner Lighting
Division of Cooper
Industries

Ward Industries

Wide-Lite
Division of Genlyte

APPENDIX B
CONSTRUCTION EQUIPMENT MANUFACTURERS CONTACTED

Wain-Roy, Inc.

Thomas Equipment Ltd.

Pierce-Correll Corporation

Aero-Lift Company

Kato Works Co., Ltd.
c/o Mitsui Machinery
Distribution, Inc.

Rockland Manufacturing
Company
Bedford Industrial Park

JLG Industries, Inc.

Manlift Marketing
Ingersoll-Rand Company

Ford New Holland, Inc.

Strato-Lift, Inc.

Major Equipment Company,
Inc.

JCB, Inc.

Liebherr-America, Inc.

Terramite Construction
Equipment Company

Gregory Manufacturing
Company

McLaughlin Manufacturing
Company

Rome Industries, Inc.

Holan Manufacturing, Inc.

Master Craft Industrial
Equipment Corp.

Altec Industries, Inc.

Workforce Products, Inc.

Intergy, Inc./Anvil
Attachments

ACS Industries, Inc.

Gradall Company
ICM Industries, Inc.

American Augers, Inc.

Augers Unlimited, Inc.

Teco, Inc.

McMillen Division
States Engineering
Corporation

Sweepster, Inc.

Sellick Equipment Ltd.

Harlo Products Corporation

Vermeer Manufacturing
Company

Massey-Ferguson, Inc.

Mark Industries, Inc.

ATI Incorporated

Mayville Engineering Company, Inc.

TRAK International, Inc.

TRAK International, Inc.

Gehl Company

Simon Aerials, Inc.

J I Case

Lowe Manufacturing Company, Inc.

Mustang Manufacturing Company, Inc.

Custom Products of Litchfield

Reach-All

Crenlo, Inc.

Angus-Palm Industries, Inc.

Simon-Telelect, Inc.

Melroe Company

Mi-Jack Products, Inc.

TT Technologies, Inc.

Farmers Factory Company

Deere Industrial Equipment Co.

Caterpillar, Inc.

Snorkel-Economy
A Figgie International Company

Simon-RO Corporation

Elliott Equipment Corporation

Auburn Consolidated Industries, Inc.

National Crane Corporation

Charles Machine Works, Inc.

Waldon, Inc.

Reedrill, Inc.

Tesmec USA, Inc.

Time Manufacturing Company

Calavar Corporation

K-D Manitou, Inc.

Kobelco America, Inc.

Alamo Group

Manitex, Inc.

General Cable Company
Apparatus Division

Kubota Tractor Corporation

Gannon Manufacturing Co., Inc.

Melfred Borzall, Inc.

UpRight, Inc.

Underground Technologies, Inc.

Esco Corporation

Genie Industries

Mitsubishi Heavy Industries, Ltd.

Load Lifter Manufacturing Ltd.

Skyjack Inc.

Dahmer Fork Lift Ltd.

FMG Timberjack Inc.

Leon-Ram Enterprises Inc.

Amida Industries, Inc.

Almand Bros., Inc.

Coleman Engineering

APPENDIX C
POINT DESIGN

This computational process utilizes the system geometry as shown in Figure C.1 and the luminaires photometric characteristics to determine the level of illumination contributed by each source. Total illumination at a point is the sum of the contribution for all luminaires. Normally luminaires at a distance of eight or more mounting heights from the point can be disregarded. From the inverse square law the horizontal illumination at point P in lux (footcandles) due to Source 1 is defined as

$$E_i = (CP_i/D_i^2) \cos \alpha_i$$

where

E_i = illuminance in lux or footcandles due to source i

CP_i = candlepower of source i in the direction of the point

D_i = distance from source i to point

α_i = angle between source i and vertical (nadir)

Since

$$\cos \alpha = MH/D$$

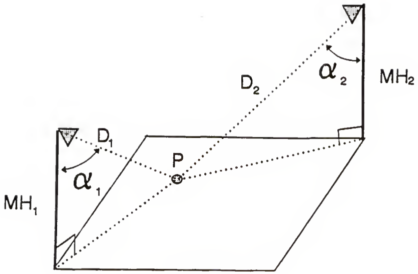


Figure C.1 Geometry of the multisource illumination problem.

where

MH = mounting height in meters or feet

the formula may be rewritten in terms of the mounting height and diagonal distance as

$$E = (CP \times MH) / D^3$$

or in terms of the mounting height and angle from the vertical

$$E = (CP \times \cos^3 \alpha) / MH^2$$

Using the above formulas, average horizontal illumination can be calculated by following four simple steps.

Step 1. On a scaled lighting plan, draw a diagonal line through a representative cross section to be called the statistical area. Starting with one end of the diagonal, mark five equally spaced points to the other end. These will be the points for analysis and five has been found to give a good approximation.

Step 2. From a scaled lighting plan determine the mounting height (MH) and horizontal distance (h) to the point of interest from the luminaire. The angle α, in degrees, can be computed from the trigonometric relationship

$$\tan^{-1} h/MH = \alpha$$

Step 3. From the photometric data for the luminaire determine the candlepower of the source in that particular direction. This will require computation of the relative position of the point with respect to the main beam axis.

Step 4. Calculate the illuminance using any one of the three formulas provided then repeat the process for all luminaires contributing to the point.

After computing the illuminance for the designated points, the average illuminance can be calculated by summing the point illuminances and dividing by the number of points.

$$E_{avg} = \sum E_i / m$$

where

E_{avg} = average maintained illumination

m = number of points calculated (recommend at least 5)

By taking the ratio of this computed average to the minimum point, the uniformity can be evaluated.

APPENDIX D
DESIGN CRITERIA

Category	Average Illuminance lux (fc) Uniformity	Area of Illumination	Activity	Examples
I	54 (5) 10:1	General illumination	Visual tasks of large size, medium contrast, or low required accuracy; General safety requirement;	Excavation Sweeping Movement of personnel
II	108 (10) 10:1	Task illumination Areas around equipment	Visual tasks of medium size, low to medium contrast, or medium required accuracy; Safety around moving equipment;	Paving Milling Concrete work
III	216 (20) 10:1	Task illuminance	Visual tasks of small size, low contrast, or high required accuracy;	Crack filling Electrical work
AREAS TO BE ILLUMINATED AROUND CONSTRUCTION EQUIPMENT				
		4.9 m x 3.3 m	Slow moving equipment	Paver (front & rear) Milling (front & rear)
		17.7 m x 3.3 m	Fast moving equipment	Roller (front & rear) Grader (front) Loader (front)

APPENDIX E
PHOTOMETRIC DATA

```
FILENAME : GE7461.IES

IESNA91
[TEST] GE 177461
[MANUFAC] GE Lighting Systems - Hendersonville, NC, USA
[LUMCAT] (not specific to a single catalog number)
[LUMINAIRE] GE POWRSPOT 20 IN
[LAMP] MET 1000-1500
[OTHER] Distribution: 5X5 (D0)
[MORE] Socket Pos: FIXED
[MORE] Comments: REVISED                       -
[MORE] Revision No:  2  Rev Date: 930216  Test Date: 91111903
[MORE] Reflector: 35-232748-02                      Refractor: FLAT GLASS
TILT=NONE
LAMPS =  1   LUMENS/LAMP = 1000        PHOTOMETRIC TYPE = 2   WATTS = 0
LUMINOUS DIMENSIONS (FEET  ): WIDTH = -1.5   LENGTH = 0      HEIGHT = 0
FACTORS : MULTIPLIER = 1          BALLAST = 1        BALLAST-LAMP = 1
NUMBER OF VERTICAL ANGLES   = 25 :   -90        TO  90       DEGREES
NUMBER OF HORIZONTAL ANGLES = 13 :   0          TO  90       DEGREES
```

HORIZONTAL ANGLES ACROSS TOP

	0	4	12	20	28	36	44	52	60	68	75	85	90
90	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0
75	1	2	1	1	1	1	1	1	1	1	1	0	0
68	5	3	5	3	3	2	2	2	2	2	1	0	0
60	28	27	24	19	13	6	5	3	2	2	1	0	0
52	82	81	68	58	43	25	13	6	3	2	1	1	1
44	97	97	97	90	79	60	34	10	3	2	1	1	1
36	183	176	156	131	98	87	58	27	8	3	1	1	1
28	523	503	414	277	153	97	76	44	14	3	2	1	0
20	800	782	672	504	273	112	87	59	17	3	2	1	0
12	1158	1118	868	645	404	129	92	68	20	3	2	1	0
4	641	944	1028	707	465	139	94	73	22	3	2	1	0
0	733	985	1008	715	468	143	94	73	22	3	2	1	0
-4	1096	1096	920	676	445	136	93	72	21	3	2	1	0
-12	859	816	738	579	319	112	89	64	19	5	2	1	0
-20	622	604	537	366	177	97	81	51	15	3	2	1	0
-28	307	297	226	161	110	88	67	35	10	3	2	1	0
-36	102	103	108	101	92	76	46	20	6	2	1	0	0
-44	90	90	89	79	71	45	22	7	2	2	1	1	1
-52	51	49	45	39	27	16	8	5	2	2	1	0	0
-60	12	10	12	8	7	5	3	2	2	1	0	0	0
-68	3	3	2	2	2	2	2	1	2	1	0	0	0
-75	3	1	1	1	1	1	1	0	0	0	1	0	0
-85	1	0	0	0	0	0	0	0	0	0	0	0	0
-90	0	0	0	0	0	0	0	0	0	0	0	0	0

```
FILENAME : GE7748.IES

IESNA91
[TEST] GE 177748
[MANUFAC] GE Lighting Systems - Hendersonville, NC, USA
[LUMCAT] (not specific to a single catalog number)
[LUMINAIRE] GE HLX
[LAMP] HPS 200-1000
[OTHER] Distribution: 6X3
[MORE] Socket Pos: FIXED
[MORE] Comments: -                                  -
[MORE] Revision No:  0  Rev Date: 901116  Test Date: 89011701
[MORE] Reflector: 35-232987-01                    Refractor: FLAT GLASS
TILT=NONE
LAMPS =  1   LUMENS/LAMP = 1000        PHOTOMETRIC TYPE = 2   WATTS = 0 .
LUMINOUS DIMENSIONS (FEET  ): WIDTH = -1.5   LENGTH = 0      HEIGHT = 0
FACTORS : MULTIPLIER = 1         BALLAST = 1        BALLAST-LAMP = 1
NUMBER OF VERTICAL ANGLES    = 33 :   -90       TO  90      DEGREES
NUMBER OF HORIZONTAL ANGLES = 11 :   0         TO  90      DEGREES

HORIZONTAL ANGLES ACROSS TOP

        0       5       15      25      35      45      55      65      75      85      90
      ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- -------
90      0       0       0       0       0       0       0       0       0       0       0
85      0       0       0       0       0       0       0       0       0       0       0
75      0       0       0       0       0       0       0       0       0       0       0
65      0       0       0       0       0       0       0       0       0       0       0
55      0       0       0       0       0       0       0       0       0       0       0
45      0       0       0       0       0       0       0       0       0       0       0
35      0       0       0       0       0       0       0       0       0       0       0
25.5  135     134     129     124     111     86      54      28      12      2       0
22.5  143     142     137     132     118     90      57      29      12      2       0
19.5  151     150     147     145     127     95      60      31      13      2       0
16.5  164     163     161     160     135     101     65      34      13      2       0
13.5  170     169     168     169     144     113     73      39      14      2       0
10.5  211     210     205     205     179     145     91      47      15      2       0
7.5   548     541     509     479     399     269     125     55      16      2       0
4.5   1155    1143    1064    961     732     436     164     67      16      2       0
1.5   1367    1352    1251    1132    831     496     182     66      16      2       0
0     1435    1420    1311    1169    862     489     176     67      15      2       0
-1.5  1256    1242    1164    1035    767     434     159     64      15      2       0
-4.5  525     519     489     455     373     254     120     54      15      2       0
-7.5  242     240     231     226     191     144     88      44      14      2       0
-10.5 175     174     171     171     144     107     70      35      13      2       0
-13.5 158     157     154     156     132     96      62      31      12      2       0
-16.5 148     147     143     140     121     88      57      29      11      2       0
-19.5 144     143     139     132     114     83      52      27      11      2       0
-22.5 133     132     128     121     105     77      48      24      11      1       0
-25.5 124     123     120     112     97      71      43      23      11      1       0
-35   0       0       0       0       0       0       0       0       0       0       0
-45   0       0       0       0       0       0       0       0       0       0       0
-55   0       0       0       0       0       0       0       0       0       0       0
-65   0       0       0       0       0       0       0       0       0       0       0
-75   0       0       0       0       0       0       0       0       0       0       0
-85   0       0       0       0       0       0       0       0       0       0       0
-90   0       0       0       0       0       0       0       0       0       0       0
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FILENAME : GE8400.IES

IESNA91
[TEST] GE 178400
[MANUFAC] GE Lighting Systems - Hendersonville, NC, USA
[LUMCAT] (not specific to a single catalog number)
[LUMINAIRE] GE POWRSPOT 20 IN
[LAMP] MET 1000-1500
[OTHER] Distribution: 5X5 (D0)
[MORE] Socket Pos: FIXED
[MORE] Comments: FULL GLARE CONTROL
[MORE] Revision No:  0  Rev Date: 930216  Test Date: 90101110
[MORE] Reflector: 35-232748-03                  Refractor: CLEAR GLASS
TILT=NONE
LAMPS =  1   LUMENS/LAMP = 1000        PHOTOMETRIC TYPE = 2   WATTS = 0
LUMINOUS DIMENSIONS (FEET  ): WIDTH = -1.5   LENGTH = 0     HEIGHT = 0
FACTORS : MULTIPLIER = 1        BALLAST = 1        BALLAST-LAMP = 1
NUMBER OF VERTICAL ANGLES   = 25 :   -90      TO  90      DEGREES
NUMBER OF HORIZONTAL ANGLES = 13 :   0        TO  90      DEGREES

HORIZONTAL ANGLES ACROSS TOP

       0       4       12      20      28      36      44      52      60      68      75      85      90
       ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ---
90     0       0       0       0       0       0       0       0       0       0       0       0       0
85     0       0       0       0       0       0       0       0       0       0       0       0       0
75     0       0       0       0       0       0       0       0       0       0       0       0       0
68     0       0       0       0       0       0       0       0       0       0       0       0       0
60     7       4       0       0       0       0       0       0       0       0       0       0       0
52     5       4       1       2       1       2       1       1       1       0       0       0       0
44     7       8       7       6       6       5       4       3       2       1       0       0       0
36     39      39      40      28      13      10      8       6       4       2       0       0       0
28     339     326     247     146     67      24      15      12      6       2       0       0       0
20     571     562     506     399     201     70      54      24      11      3       0       0       0
12     636     644     644     553     353     122     79      36      16      5       1       0       0
4      814     824     745     658     466     152     85      46      19      5       2       0       0
0      726     801     827     692     492     160     87      48      20      5       2       0       0
-4     863     903     885     725     491     152     86      46      19      4       3       0       0
-12    958     955     854     719     407     127     83      43      19      4       4       1       0
-20    805     807     738     522     254     112     75      40      18      4       4       1       0
-28    517     495     372     237     147     99      61      33      16      5       5       1       0
-36    139     137     136     120     104     78      47      25      12      5       6       2       0
-44    98      96      93      90      83      50      31      17      8       4       4       3       2
-52    70      66      62      57      47      25      16      12      7       3       4       2       1
-60    21      22      25      22      17      12      11      8       6       3       4       2       0
-68    12      10      9       8       9       8       6       7       5       2       3       2       1
-75    7       5       6       6       7       6       6       5       5       4       2       2       2
-85    2       2       2       2       3       3       3       3       2       2       2       2       2
-90    0       0       0       0       0       0       0       1       0       1       2       2       2
```

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FILENAME : GE8572.IES

IESNA91
[TEST] GE 178572
[MANUFAC] GE Lighting Systems - Hendersonville, NC, USA
[LUMCAT] (not specific to a single catalog number)
[LUMINAIRE] GE SBN
[LAMP] MET 100-175 MED
[OTHER] Distribution: 3X4
[MORE] Socket Pos: FIXED
[MORE] Comments: -                                      -
[MORE] Revision No:  0  Rev Date: 930217  Test Date: 91041904
[MORE] Reflector: -                               Refractor: FLAT GLASS
TILT=NONE
LAMPS =  1   LUMENS/LAMP = 1000        PHOTOMETRIC TYPE = 2   WATTS = 0
LUMINOUS DIMENSIONS (FEET  ): WIDTH = -1.5   LENGTH = 0      HEIGHT = 0
FACTORS : MULTIPLIER = 1          BALLAST = 1        BALLAST-LAMP = 1
NUMBER OF VERTICAL ANGLES   = 31 :   -90       TO  90       DEGREES
NUMBER OF HORIZONTAL ANGLES = 17 :   0         TO  90       DEGREES

HORIZONTAL ANGLES ACROSS TOP
```

	0	1.5	4.5	7.5	10.5	13.5	16.5	19.5
90	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
65	4	3	0	0	0	0	0	0
55	30	30	30	29	28	27	25	24
45	75	76	78	77	76	75	72	66
42.5	78	82	82	82	78	78	75	71
37.5	90	93	90	93	90	86	86	82
32.5	112	116	116	112	108	104	97	93
27.5	168	172	172	168	153	138	123	116
22.5	362	369	377	332	261	205	168	146
17.5	765	772	746	589	418	295	228	187
12.5	1160	1153	1022	791	548	381	284	231
7.5	2026	1989	1713	1239	798	515	351	276
2.5	3306	3212	2597	1735	1063	642	407	295
0	3727	3604	2765	1772	1056	631	399	295
-2.5	3362	3250	2410	1556	974	601	395	295
-7.5	1541	1444	1123	866	634	459	340	276
-12.5	657	664	660	578	440	343	284	239
-17.5	616	612	608	511	381	295	246	216
-22.5	560	567	578	478	362	276	224	198
-27.5	489	500	504	414	313	243	198	179
-32.5	366	366	332	291	243	194	168	157
-37.5	183	183	187	183	168	149	138	134
-42.5	116	116	116	123	119	116	116	116
-45	97	99	103	102	100	98	97	97
-55	71	70	67	68	69	70	70	69
-65	37	37	37	36	35	34	33	32
-75	0	1	4	3	2	1	0	0
-85	0	1	4	3	2	1	1	2
-90	0	1	4	3	2	1	1	4

	22.5	25.5	35	45	55	65	75	85	90
90	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0
55	23	21	11	4	0	0	0	0	0
45	61	56	49	34	11	0	0	0	0
42.5	71	71	54	43	22	1	0	0	0
37.5	78	78	66	62	45	3	0	0	0
32.5	93	90	76	74	65	6	0	0	0
27.5	108	104	88	79	84	9	0	0	0
22.5	134	127	102	90	96	15	1	0	0
17.5	164	153	122	104	101	22	3	0	0
12.5	198	179	136	115	105	27	4	0	0
7.5	228	201	148	120	107	29	4	0	0
2.5	246	213	156	127	108	28	4	0	0
0	239	213	160	131	108	26	4	0	0
-2.5	243	213	162	132	108	26	4	0	0
-7.5	235	209	161	132	108	25	3	0	0
-12.5	213	194	156	129	108	23	1	0	0
-17.5	194	179	149	126	108	22	0	0	0
-22.5	179	168	142	124	108	22	0	0	0
-27.5	168	160	132	118	102	19	1	0	0
-32.5	153	146	118	106	88	14	3	0	0
-37.5	134	127	106	95	73	9	4	0	0
-42.5	112	108	96	84	54	6	4	0	0
-45	97	97	90	78	45	4	4	0	0
-55	68	66	52	41	4	4	0	0	0
-65	31	29	15	4	0	0	0	0	0
-75	0	0	0	0	0	0	0	0	0
-85	3	4	0	0	0	0	0	0	0
-90	6	8	0	0	0	0	0	0	0

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